

# Introduction to Plastics Recycling

*Second Edition*

Vannessa Goodship





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# Preface

Although recycling has a very long history, it is only relatively recently that environmental protection and waste management issues have come to the forefront of both public and political awareness. The removal of plastics from both the waste streams and from landfill have since become areas of major interest.

Outside the fields of expertise, generally little is known about either plastics or their recyclability. A number of specialist books are available, however none has addressed the need to cover the pertinent principles at an introductory level.

This book describes the options for recycling plastics with special focus on mechanical recycling. It touches on all the major problems associated with recovering and recycling plastics at a level intended to be accessible to any reader with an interest in this field, whatever their background. It also looks at some of the broader issues surrounding successful waste management of plastics.

## **Updated for the Second Edition**

Since the first edition was published in 2001, great strides have been made in increasing recycling rates worldwide. There has been expansion of infrastructure in the UK to support plastic recycling. Major achievements have been made in gaining widespread public support and participation for recycling schemes and specifically the need to manage waste on an individual household level.

Council recycling of plastic bottles has become widespread\* and the practice of providing free plastic carrier bags by supermarkets has become an issue for the environmentally conscious shopper.

Biopolymers are expected to have a major impact on plastic markets in the future and therefore some of the issues of biodegradability *versus* recycling are expanded in this second edition, as is the wider context of life cycle analysis and legislation. There is still much to do, but if this book is updated in the future for a third edition, hopefully a fully functional plastic recycling system will be operating nationwide.



\* My own local municipal waste disposal site. No separate plastics collection (yet!)  
(Source: N. Goodship)

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My dad for knowing nothing about plastics and thereby being a willing guinea pig. His good humour, comments and bafflement at anything to do with chemistry were invaluable.

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All photographs were expertly taken by Graham Canham, unless otherwise stated.

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**Vannessa Goodship**

University of Warwick, 2007



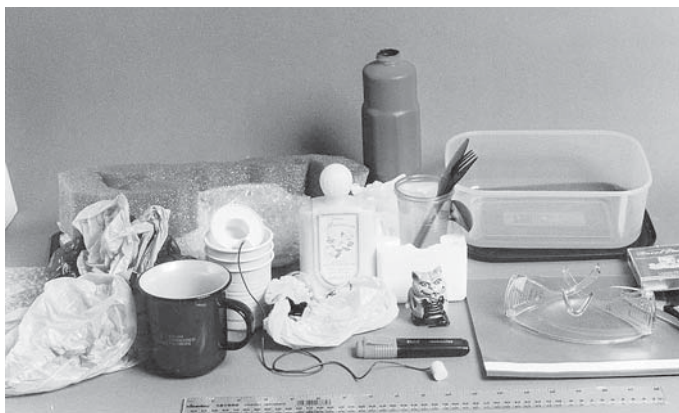
# 1 Introduction

It would be hard to imagine a modern society today without plastics. Plastics have found a myriad of uses in fields as diverse as household appliances, packaging, construction, medicine, electronics, and automotive and aerospace components. As can be seen from this list, plastic technology can be applied with great success in a variety of ways.

So what makes plastic such a versatile material?

The reason for its success in replacing traditional materials such as metals, wood and glass in such a diverse range of applications, is the ability to modify its properties to meet a vast array of designers' needs. This, plus the ease with which plastics can be processed, makes them ideal materials for the production of a variety of components. A quick rummage around the office soon found a whole host of plastic items, the result is shown in **Figure 1.1**. Look around and you'll be surprised to see just how many different uses plastics have found and how big a market the plastic industry supports.

The plastic material used to make many of these products is what is called 'virgin' grade. These are materials which have come straight from the polymer manufacturer to the factory and have not yet been processed. If these materials later come to be reprocessed, they are then called 'recyclates'. However not all plastic materials are reprocessed, most are simply thrown away, leading to the need to dispose of them. A continued increase in the use of plastics has led



**Figure 1.1** Various plastic items

to an increasing amount of plastics ending up in the waste stream. To get an idea of the size of the market, the Western European consumption of plastics in 2005 was 43.5 million tonnes [1], with the UK accounting for 4.8 million tonnes [2] of this with the majority of post consumer plastic waste ending up in landfill.

‘The UK currently recycles or recovers approximately 19% of all plastic consumed. This is set to increase to over 25% by 2010 [3].’

Management of waste is one of the major problems facing modern society and is not just limited to plastics. However, a combination of legislative measures and government initiatives, the increasing cost of landfill disposal and public interest in support of recycling has meant that plastics recycling must increase. Generally, plastics are made from crude oil. Recycling of plastics therefore helps to conserve this natural resource.

Any strategy for waste management is based around three guidelines.

- Avoidance, i.e., reducing and, if possible, avoiding producing waste at source. No waste = no problem.
- Reclamation, the recovery of materials from the waste stream for recycling.
- Elimination, the disposal of non-recyclable materials, for example by landfill.

The second point can be applied to the problems of plastic waste by reclaiming material that is destined for landfill. Hence, plastic material recovered from the waste stream is termed ‘reclaim’. A summary of the terms introduced so far is given in **Table 1.1**.

<b>Table 1.1 Summary of common terms</b>	
<b>Term</b>	<b>Meaning</b>
Virgin grade	A material that has not yet been processed
Recyclate	A material that has already been processed
Reclaim	A material reclaimed from the waste stream for recycling

A material is reclaimable when both a treatment technology and a market for the resulting new material are available [3]. This book concentrates on the reclamation and recycling of plastics. There are several options for how this can be done: reuse, mechanical recycling, feedstock recycling and energy recovery. These are defined next.

**Reuse:** the most common examples of reuse are with glass containers, where milk and drinks bottles are returned to be cleaned and used again. Reuse is not widely practised in relation to plastic packaging - plastic products in general tend to be discarded after first use. However, there are examples of reuse in the marketplace. For example, a number of detergent manufacturers market refill sachets for bottled washing liquids and fabric softeners. Consumers can refill and hence reuse their plastic bottles at home.

**Mechanical recycling:** also known as physical recycling. The plastic is ground down and then reprocessed to produce a new component that may or may not be the same as its original use.

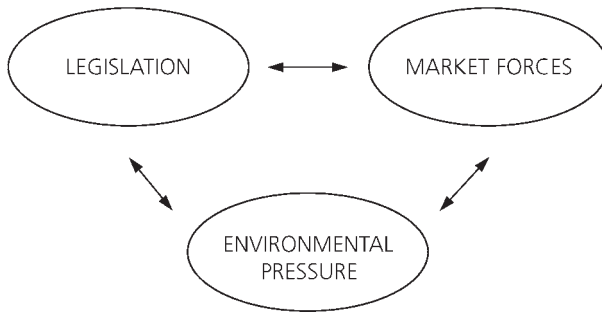
**Feedstock recycling:** the polymer is turned back into its oil/hydrocarbon component for use as raw materials for new polymer production. This is also known as chemical recycling.

**Energy recovery:** the materials are incinerated to recover their inherent energy.

Mechanical recycling is the most widely practised of these methods and will be the focus of much of the further chapters. However, the others are valuable options for waste disposal, especially for materials that do not meet the criteria for mechanical recycling for reasons of practicality or cost-effectiveness.

A number of technologies are available for recovering and recycling plastics. Some are currently in use by industry and capable of processing large quantities of material in a cost-effective manner, whilst others currently exist only in laboratories. Plastic recycling is an area that is constantly developing to try to meet the often competing demands of legislation, market forces and environmental pressure. The inter-relationship is complex and is illustrated in **Figure 1.2**. No manufacturer wishing to stay in business can recycle materials if it is not profitable to do so. Recycled plastics are used





**Figure 1.2** Interrelationships affecting recycling activity

in the same market in which they originated. They replace and compete against virgin materials. The price recycle can command will depend on both the price of the virgin materials and the quality of the recycle. The price of virgin materials can vary greatly as it is linked to both oil prices and supply and demand within the market. This in turn means that the price that recycle can command varies greatly.

Environmental pressure may create a demand from the consumer for recycled goods. By creating such a market, a manufacturer can see a profit to be made, and will therefore begin to produce and sell recycled goods. This business will also be subject to the effects of market forces, supply and demand. Environmental pressure may also result in legislation forcing manufacturers to use recycled materials. In this case, a market may not exist already and this legislation will impact upon the ‘natural’ market force. The result may be less profitable and require subsidies to kick-start such activity. For long-term growth however, the activity must be self-supporting.

A fully sustainable infrastructure for the recycling and recovery of plastics is required if the vast quantities of plastic material

available are to be diverted from landfill. However, this will occur only when the demand is created for the end product materials and it is economically viable to recycle them. Currently, this has meant that recycling activities need to be subsidised if they are not commercially profitable. Therefore it is paramount that the plastic industry continues to educate the public and potential recycle users in order to create and develop the supply and demand for these materials.

Before recycling methods are discussed in more depth, a familiarity with some of the fundamentals of polymer science is required. This will be introduced in Chapter 2.

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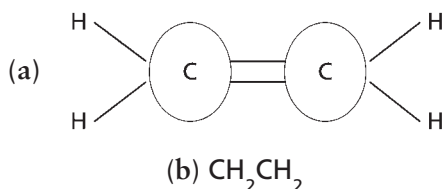
# 2

## Back to Basics

To recycle a plastic it is necessary to have an understanding of both what the material is, and how it is likely to behave. Plastics are made up of polymers and other materials that are added to give the polymer increased functionality. Some of these materials will be introduced later in the chapter, but first a brief introduction to polymers is required.

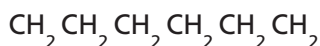
### 2.1 Polymers

Polymers take their name from two Greek words: poli which means many and meros which means parts. This is because they are made up of a number of repeat units, called monomers. The simplest and most commonly used monomer is ethylene. Chemically it consists of two carbon atoms (C) and four hydrogen atoms (H). It can be represented in the two ways shown in **Figure 2.1**. The lines shown in **Figure 2.1(a)** represent the bonds that exist between the atoms to form a molecule.



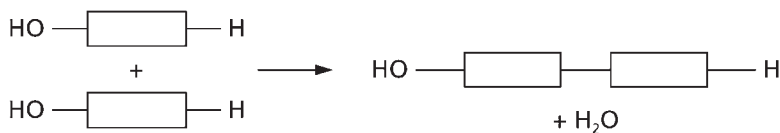
**Figure 2.1** An ethylene molecule

It is the existence of the double bond between the carbon atoms in ethylene, which allows the creation of the many-ethylene, or, to use the proper term, polyethylene. This happens when the monomers are combined by a process called polymerisation to form a chain such as the one shown in **Figure 2.2**. A chain of useful polymer may consist of 200-2,000 of the monomers joined together. This particular type of polymerisation is called addition polymerisation. The ethylene monomer is termed an unsaturated monomer. The term unsaturated applies to the double bond that exists between the carbon atoms.



**Figure 2.2** Polyethylene molecule

Another method of synthesising polymers is called polycondensation. Here, the reaction mechanism involves reactive end groups on the monomers that can bond together and expel water. An example of how this works is shown in **Figure 2.3**.



**Figure 2.3** Polycondensation polymerisation

Common examples of both types of polymers are shown in **Table 2.1**.

Table 2.1 Examples of polymers made from two different polymerisation mechanisms	
Polymers from unsaturated monomers	Condensation polymers
Polyethylene (PE)	Nylon 66 (Polyhexamethylene adipamide)
Polypropylene (PP)	Polyethylene terephthalate (PET)
Polystyrene (PS)	Polyurethane (PU)
<i>Reaction mechanism: breaking of double bond</i>	<i>Reaction mechanism: reactive end groups that join, expelling water</i>

The long chains that are formed in polymerisation are called macromolecules. The repeat units of some common polymers are shown in **Table 2.2**. A polymeric material may have chains of various lengths or repeat units, the average size of which determines the molecular weight. The properties of the polymer are strongly linked to molecular weight and it is necessary to match the molecular weight, material properties and flow characteristics in order to shape the material during processing and give the desired final product.

The polymer content within a plastic can vary widely from less than 20% to nearly 100%. Those plastics consisting virtually entirely of polymers are termed ‘prime grades’. The level and type of the other additives used depends on the application for which the plastic is intended. In the USA over 18,000 different grades of polymer material are available.

Plastics can be subdivided into three main categories: thermoplastics, thermosets and elastomers. This distinction is based on both the molecular structure and the processing routes


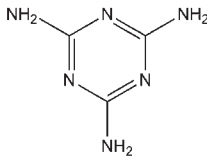
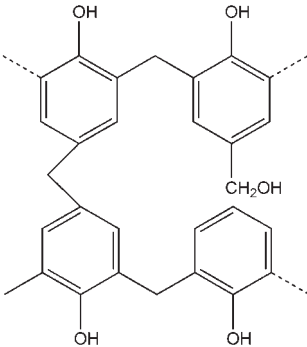
Table 2.2 Characteristic structures of common polymers	
Polymer	Repeat Unit(s)
Polyethylene	$\text{-(CH}_2\text{—CH}_2\text{)}_n$
Polypropylene	$\text{-(CH}_2\text{—CH)}_n$   CH <sub>3</sub>
Polystyrene	$\text{-(CH}_2\text{—CH)}_n$   
Polyamide 6	$\text{-(C(=O)—(CH}_2\text{)}_5\text{—NH)}_n$
Polyamide 55	$\text{-(C(=O)—(CH}_2\text{)}_4\text{—C(=O)—NH—(CH}_2\text{)}_6\text{—NH)}_n$
Polyethylene terephthalate	$\text{-(CH}_2\text{—CH}_2\text{—O—C(=O)—C}_6\text{H}_4\text{—C(=O)—O)}_n$
Polyvinyl chloride	$\text{-(CH}_2\text{—CH)}_n$   Cl
Epoxy resin	$\text{-(O—C}_6\text{H}_4\text{—C(CH}_3\text{)}_2\text{—C}_6\text{H}_4\text{—O—CH}_2\text{—CH(OH)—CH}_2\text{)}_n$
Melamine-formaldehyde resin	<div style="display: flex; align-items: center; justify-content: center;"> <div style="text-align: center; margin-right: 20px;"> <math>\text{H}</math>   <math>\text{C=O}</math>   <math>\text{H}</math> </div> <div>  </div> </div>

Table 2.2 Continued	
Phenolic resin	
Unsaturated polyester	Unsaturated polyester resins are formed by the reaction of a polyfunctional acid with a polyfunctional alcohol, where one monomeric group contains double bonds, so that the resulting polymer is unsaturated.
Polyurethane	Polyurethane is formed by reacting together a diisocyanate and a polyether or a polyester, which form a urethane linkage.

that can be applied. It also relates to recycling routes, as each of the categories needs a different approach to utilise recovery potential. Elastomers are beyond the scope of this book and will not be dealt with here. Thermoplastics and thermosets will now be introduced.

## 2.2 Thermoplastics

These materials melt and flow when heated and solidify as they cool. On subsequent reheating they melt and regain the ability to flow. This means they can be reprocessed and hence recycled

<b>Table 2.3 Common thermoplastics and their applications</b>		
<b>Thermoplastic Polymer</b>	<b>Applications</b>	<b>Lifetime range</b>
HDPE	Packaging, pipes, tanks, bottles, crates	Packaging: 2 years Pipes: 30 years
LDPE	Packaging, grocery bags, toys, lids	Packaging: 2 years
LLDPE	Packaging	2 years
PP	Caps, yoghurt pots, suitcases, tubes, buckets, rugs, battery casings, ropes	Packaging: 2 years Battery casings: 10 years
Polystyrene (PS)	Mass produced transparent articles, yoghurt pots, fast food foamed packaging, cassettes	Packaging: 5 years Cassettes: 10 years
Polyamide* (PA)	Bearings, gears, bolts, skate wheels, fishing lines, carpets, clothing	10 years
Polyethylene terephthalate (PET)	Transparent carbonated drink bottles	5 years
Polyvinyl chloride (PVC)	Food packaging, shoes, flooring	5 years
* Also known as Nylon		

by remelting them. Thermoplastics are used to make consumer items such as drinks containers, carrier bags and buckets. The most common thermoplastic materials and their applications are shown in **Table 2.3**.



### 2.2.1 Polyolefins

The term polyolefin covers all polymers made from monomers with linear C=C double bonds such as the ethylene molecule shown in **Figure 2.1**. This includes polymers such as low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE) and polypropylene. Common uses of these materials are shown in **Table 2.3**.

The different types of polyethylene derive from differences in the polymer chains, which in turn result in variations in melting points, densities, properties and therefore applications (see **Table 2.4**). It may be necessary to specify the type of polyethylene being referred to, e.g., HDPE, LDPE or LLDPE.

Table 2.4 Melting points and densities of common polyolefins		
Polyolefin	Melting Point (°C)	Density (g/cm <sup>3</sup> )
LDPE	115	0.92
LLDPE	123	0.92
HDPE	130	0.95
PP	170	0.90

### 2.2.2 Polyamides

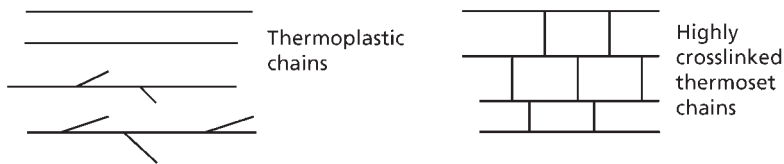
Polyamide is the term used to describe polymers containing the amide group. It is also commonly known as Nylon, which was the generic name given to the material by DuPont, the company that developed this material in the 1930s. By 1940, the whole of the USA was supplied with Nylon stockings such was the impact of this material. The most common types of polyamide

are designated polyamide 6 and polyamide 66, they may also be written PA 6 or PA 66. The numbers represent the chemical makeup of the polymer chains, an explanation of which is beyond the scope of this book. Less commercially important polyamides include polyamide 11 and polyamide 12. The properties of polyamides can vary greatly and it is important to be clear on the type of polyamide material being discussed. As an indication of the differences between these materials, the melting points and densities of the most common polyamides are given in **Table 2.5**.

<b>Table 2.5 Melting points and densities of common polyamides</b>		
<b>Polyamide</b>	<b>Melting Point (°C)</b>	<b>Density (g/cm<sup>3</sup>)</b>
Polyamide 6	233	1.13
Polyamide 66	265	1.14
Polyamide 11	180	1.04
Polyamide 12	180	1.02

## **2.3 Thermosets**

Thermoset materials are melt processed, often in a similar manner to thermoplastics. However, once formed and cooled they cannot be reprocessed, they decompose before they can melt. Therefore, they cannot be reprocessed in the same way as thermoplastics. This is because they are chemically crosslinked by a process termed ‘curing’. The result is a highly dense molecular network making the material stiff and brittle. The differences in the arrangement of molecules between thermoplastics and thermosets can be seen in **Figure 2.4**.



**Figure 2.4** Arrangements of thermoplastic and thermoset molecular chains

Thermosets are often used where their strength and durability can be utilised. Common thermosets and their applications are shown in **Table 2.6**.

If thermosets cannot be reprocessed by melting, then how do we reprocess them?

Table 2.6 Common thermoset materials		
Thermoset Polymer	Application	Lifetime range
Epoxy	Adhesives, electrical insulation	10 years +
Melamine-formaldehyde resin	Heat resistant laminate surfaces, i.e., kitchen worktops	10 years +
Phenolic	Heat resistant handles for pans, irons, toasters	10 years +
Polyurethane (PU)	Rigid or flexible foams for upholstery and insulation	10 years +
Unsaturated polyesters	Partitions, toaster sides, satellite dishes	10 years +

Much research has been done, looking for methods to recycle these materials. This will be further elucidated in Chapter 8.

## **2.4 The Formulation of Plastics**

It was stated earlier in the chapter that plastics are mixtures of polymers and other materials. There are many additives commercially available that can be mixed with polymers. For example, glass or carbon fibre reinforcement gives them increased strength. Flame-retardants can be added for flame resistance. Plastics can be coloured with pigments for aesthetic or technical purposes, or they can be made more heat and light resistant by the use of stabiliser additives. These are just a few examples of the numerous possibilities. In addition, the levels of each of these additives can also be varied. It is easy to see how so many grades of plastic have come to exist. It is also, hopefully, becoming apparent how plastics have been able to compete so successfully with other materials as diverse as glass, metal and wood. A list of some of the more common plastic additives is given in **Table 2.7**.

Foaming agents are used to make plastic foams, for example, for making upholstery cushions or fast food packaging containers. Powdered blowing agents are mixed with the plastic prior to processing and decompose on heating, giving off gas, which causes the plastic to foam. Foaming gives plastics a number of unique properties such as reduced density and heat and sound insulating properties. Foaming can also be achieved by introducing a gas such as nitrogen into the melt.

Mould release agents are often incorporated into a plastic formulation to aid the processing of the material. During moulding, plastic parts may become stuck in the moulds making production time consuming, less cost effective and affecting the quality of the final components. Mould release agents impart non-stick properties

Table 2.7 Common additives for plastics	
Additive	Purpose
Glass fibre	Increased strength and stiffness
Calcium carbonate	Filler used for cost reduction: much cheaper than polymer
Flame retardant	Increased fire resistance
Light stabilisers	Increased resistance to degradation due to light exposure
Heat stabilisers	Increased resistance to degradation from elevated temperature exposure
Pigments	Give colour, improve aesthetic properties
Foaming agents	Lightness and stiffness
Mould release agents	Processing aids
Anti-static additives	E.g., prevent dust build up on consumer items
Plasticisers	Reduce viscosity, aid processing

ensuring that components can be easily removed from moulds during the production cycle.

Plasticisers are low molecular weight additives, which are used to lower the viscosity of materials and aid processing. The most common usage of plasticisers is in PVC, where they are incorporated to give the rigid PVC more flexibility.

## 2.5 Why Does Recyclate Always Seem to be Black?

Imagine a single common polymer, for example polypropylene, which is the most commercially important of all polymers. Now consider how we could modify it with additives. Suddenly we

have an awful lot of different materials with different properties and colours.

What would the properties be if they were all blended together?

Just considering colour alone, the variation in the recyclate would be enormous. It is probably not a good thing for marketing a recyclate product if you cannot guarantee what colour it will be from one day to the next. One way to ensure the new application is of a consistent colour is to make it all black. Black pigments are very good at masking other colours underneath (and contaminants). A relatively small quantity of black pigment will ensure that the recyclate comes out a constant black colour whatever the original colour was. It may not be ideal but it is one solution.

Of course, not all recyclates are black, some waste streams remain relatively unmixed in terms of variances in colour. Examples are recycled crates or unmixed waste streams of transparent bottles. However, when mixtures of colours find their way into the waste stream in a way that cannot be controlled, then the chances are that it will be coloured black when it is reprocessed.

## **2.6 What Are Recyclates Used For?**

With the exception of food contact and medical products for which many recyclate materials are unacceptable, recyclates can be used in a variety of ways. Refuse sacks are an especially good outlet for recyclate materials. These products, consisting mainly of LDPE, may be made entirely of recyclate materials. Products like this are rare and the majority of recyclate containing products are blended with virgin materials. Supermarket carrier bags also often have a percentage of recyclate materials in them. The limiting factor here may be colour. Refuse bags, which are mainly, but not exclusively, black are not so problematic. There are processing technologies

such as co-injection moulding and multi-layered extrusion blow moulding where the recyclates can be encapsulated within virgin materials, removing the colour issues. This reduces the quantity and hence the costs of virgin raw material required. For cost purposes many products may contain some quantity of recyclate material, often this is not disclosed by the manufacturer. Some examples of products which commonly use recyclates are shown in **Table 2.8**.

Comparing **Table 2.8** to **Table 2.3**, apart from the food contact restrictions, the applications for recyclates are quite similar to the applications for virgin materials. Mixed plastic waste (MPW) appears in this table. This is a material consisting of various plastic wastes rather than just one single polymer type. The outlets for materials of this type tend to be limited to wood replacement products for reasons that will become apparent later.

Table 2.8 Examples of outlets for recyclates	
Thermoplastic Polymer	Recyclate Applications
HDPE	Non-food bottles
LDPE	Refuse bags, carrier bags
PVC	Non-food bottles, cable conduits, ducts and sewage pipes, multi-layer PVC flooring
PP	Battery casings, bumpers, garden furniture
PS	Audio and video cassettes, compact disc trays, coat hangers
PA	Fibre for carpets
PET	Non-food bottles, fibres for clothing, sleeping bags
Mixed Plastic Waste (MPW)	Wood replacement products such as pallets and fencing

## **Suggested Further Reading**

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3. T.A. Osswald and G. Menges, *Materials Science of Polymers for Engineers*, Carl Hanser Verlag, Munich, Germany, 1996.
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# 3 The Effects of Processing on Thermoplastics

We now know what plastics are made of, some of the things virgin materials are used for and the differences between thermoplastic and thermoset materials. It is here that we begin to concentrate on thermoplastics and examine what happens to them when they are processed. Methods are described in detail in Chapter 6. Processing in its simplest form is the act of melting, forming and then solidifying the melt. During this procedure three things need to be considered [1].

- Deformation processes, which enable the product to be formed.
- Heat and heat transfer, which enable the polymer to melt, flow and then solidify.
- Changes to structure and properties as a result of processing.

We will begin with a study of deformation processes and for this, we need to consider rheology.

## 3.1 Rheology

Rheology is the study of deformation and flow. Consider the following examples of flow:

1. Squeezing toothpaste through a tube,

2. Tipping honey from a spoon, and
3. Pouring water into a glass.

The toothpaste, honey and water all have different viscosities. The toothpaste is the most viscous, the water the least. Viscosity means the resistance to flow.

In viscous flow, a material continues to deform as long as a stress is applied.

To put it more simply, in the case of the toothpaste tube, the toothpaste is squeezed out only for as long as we squeeze the tube.

Consider the toothpaste again, when it is squeezed and then released it does not return to the original shape. A rubber ball however, does return to its original shape when released due to its elastic properties, and likewise polymer melts will try to return to their original shape when stress is removed. So polymers combine both viscous and elastic properties and demonstrate what is called a viscoelastic response to stress.

Polymers are more viscous than most liquids.

Polymers are more elastic than most solids.

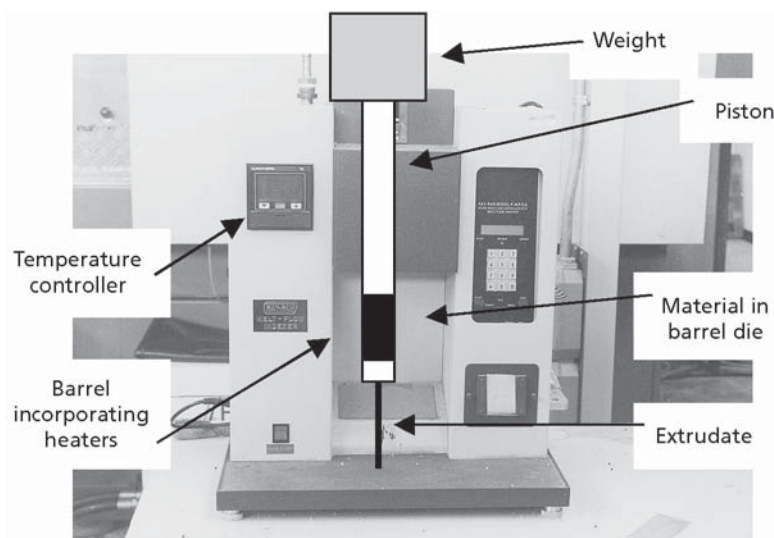
The interaction between viscosity and elasticity frequently determines the success of any processing operation. Processing must take into account not only how the polymers flow in their molten state but also how they change as the temperature goes up and down and the polymers melt and solidify.

Two very common materials in commercial use are low density polyethylene (LDPE) and polyamide (PA).

As LDPE is heated, it turns from a solid, to a viscous gummy liquid and then to a mobile fluid as temperature is increased. PA on the

other hand turns quite suddenly from a solid to a low viscosity (watery) fluid. It is important to understand that polymers may react differently to the heat and stress applied to them, in order to find the most suitable methods to form them.

A cheap and simple method of determining and comparing the flow of melts under standard conditions is a Melt Flow Indexer. This works in a similar way to squeezing toothpaste from a tube. A vertical load is applied to a piston and the polymer melt is squeezed through a die, this is shown in **Figure 3.1**. The amount of polymer that is extruded in a fixed time gives a measure of the flow as a melt flow index (MFI). A highly viscous material will have a low MFI, a low viscosity material will have a high MFI.



**Figure 3.1** Basic parts of an MFI machine (a Ray-Ran machine is shown in this photograph)

We will see later that as a polymer degrades, its viscosity becomes lower. Charting the changes that occur during repeated recycling of material can give a measure of the degradation processes occurring. MFI can provide a cheap and simple method of measuring this change.

### **3.2 Heat**

A thermoplastic cannot flow in its solid state. To enable it to flow it needs to be heated above its melting point ( $T_m$ ). Some melting points of common plastics are shown in **Table 3.1**. Just from these examples, a wide range of melting points can be clearly seen. Once a polymer is heated above the melting point the viscosity will decrease as the temperature increases. The rate of this change varies, according to the particular type of material. Eventually the polymers will reach a point where they become thermally unstable and start to degrade. Generally, this shows itself as a discolouration with the melt turning yellow or brown. This can be a problem when processing mixed plastic fractions, because of the difference in processing temperature required to melt the various fractions contained in a heterogeneous mixture.

<b>Table 3.1 Melting points of common thermoplastics</b>	
<b>Polymer</b>	<b><math>T_m</math> (°C)</b>
Polyethylene (PE)	135
Polypropylene (PP)	170
Polystyrene (PS)	240
Polyethylene terephthalate (PET)	245
Polyamide 6 (PA6)	233

Heterogeneous and the opposite, homogeneous mixtures, have great importance in plastic recycling.

First, let's define the terms used:

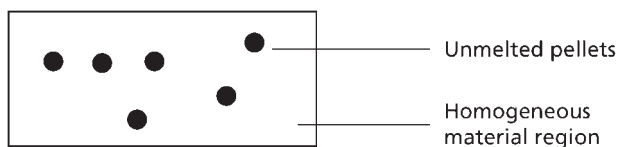
- Homogeneous: a material with the same properties at all points.
- Heterogeneous: a material consisting of two or more phases.
- A phase: a physically homogeneous, mechanically separable portion. Think of a phase as a distinct identifiable region.

To keep it simple at this stage think of a mixture of more than one plastic as a heterogeneous mixture and a mixture of the same plastic as a homogeneous plastic. These concepts will become more clearly developed in later chapters, for now, let's get back to plastic mixtures.

Look at **Table 3.1** and then consider a waste fraction that contains 90% PE and 10% PA6.

If we process the waste at a temperature suitable for the PE fraction (135 °C), the PA6 will not melt (233 °C). The unmelted fraction would be carried along in the melt stream, and what you would get in your final product would be a homogeneous fraction and discrete pellets of unmelted material as illustrated in **Figure 3.2**, so, the final product is heterogeneous. The unmelted pellets would be points of mechanical weakness in the moulding. It is simpler to imagine that these pellets are just filling holes. They serve no other purpose. Only if the unmelted regions are very small would they not be detrimental to the material properties, this idea will be further developed in later chapters.

Consider the mixture of PA6 and PE again.



**Figure 3.2** Moulding containing unmelted polymer

What happens if the mixture is processed just above 233 °C, so that both fractions melt?

In this case, both fractions would melt, but the temperature is much higher than PE would generally be processed at, and it may begin to thermally degrade. As will be shown later, degradation of this type, caused by elevated processing temperatures, can cause a considerable loss in the mechanical properties of the plastic.

Is this sample now homogeneous?

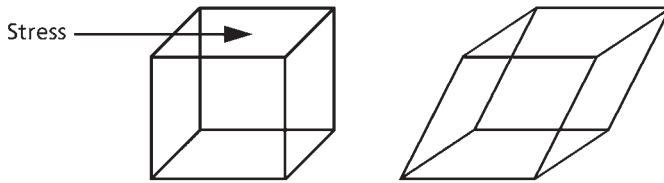
No, look back at the definition, it still consists of a mixture of two plastics and is therefore still heterogeneous. It could also, potentially, be subject to degradation during processing. Therefore, the properties of these materials may be affected. Any degradation process occurring in the mixture could have a detrimental effect on the mechanical properties of the blend.

Thus, in processing mixed wastes, even if you know what polymers they consist of, how do you decide on the best conditions to process them?

Sometimes, experiments will be required to find the optimum conditions. Methods will be discussed in the following sections.

### 3.3 Physical and Chemical Changes

As well as the effects of heat on the polymer, the effects of shear also need to be considered. Shear is a type of force that involves exerting stress across the surface of the polymer, while in effect, the base of the polymer is untouched. This action is shown in **Figure 3.3**. The action of shear, like temperature, causes a decrease in viscosity. This is due to the shearing action causing mechanical damage and breakage to the polymer chains. At very high levels of shear this leads to degradation.



**Figure 3.3** Shearing flow

With this in mind, good thermal stability is a requirement for most polymer processing operations, as the combined action of heat and shear can produce degradation. The effect of this is chain breakage. The length of the chain is related to the molecular weight, and the molecular weight affects the properties. Therefore any change in chain length will affect:

- Molecular weight and viscosity.
- Tensile and impact properties.

Combined heat and shear can also result in:

- Change in colour (yellow or brown discolouration).
- Reduced fibre length in glass filled materials.

Consideration must be given to the residence time of the material in the processing machine. A typical residence time may be 3-5 minutes. Longer residence times may cause thermal deterioration. Also, within a closed loop cycle, scrap material may be reground and reprocessed many times.

Shear stress is not just confined to the polymer in its molten state. Shear is also exerted during the actions of grinding and cutting of the solid materials. So shear force is not just applicable to the plastic in its molten state but also in its solid one.

The way this affects the material properties will depend on the specific material response each time it undergoes degradation processes and how the regrind is blended for example, with new material. Mechanical shear is the primary mechanism for deterioration in mechanical properties, such as tensile strength. Mechanical grinding in order to reduce the size of solid plastics is the second most important factor. Since the actions of mixing, processing and size reduction have a shearing effect upon the polymer material, ways must be found to assess this level of damage to the plastic. There are a number of methods that can be used. An outline of suggested methods is given on the following pages.

### **3.4 Assessing Property Deterioration Caused by Repeated Cycling by Injection Moulding**

Simple experiments can be performed to assess the effects of processing on properties.

Mouldings should be produced using the same conditions as used for full production to get useful and representative results.

The following three experimental procedures explore the recycling limitations of a plastic material. They identify the limits of



reprocessing, as regards retention of mechanical and rheological properties, and allow the limits of recyclability to be assessed in terms of comparisons of closed loop recycling (Method 1A) and blending with virgin materials (Method 1B and Method 2). The results of these experiments can be used to determine if and when virgin material needs to be introduced into the recyclate mixtures and the likely properties of the resulting components.

**Method 1A:** Closed loop recycling with regrind only

- i. Mould 100% virgin material, keep some mouldings back for evaluation
- ii. Regrind a quantity of this 'first pass'
- iii. Mould and keep some mouldings back for evaluation
- iv. Repeat for required number of passes, e.g., 'second pass', 'third pass', etc.
- v. Carry out evaluations on virgin and all passes (mechanical and/or rheological as required)
- vi. Examine the results

A second set of useful experiments concern the effects of blending recyclates with virgin materials. This will depend on the results of the first set of experiments. For example, there may be no change after two passes, but the third pass may show a significant drop in properties. At the stage that the properties fall, for the sake of clarity we will say that in this case it is the third pass, blending with virgin material is used to boost the properties of the final mouldings.

**Method 1B:** Blending with virgin material

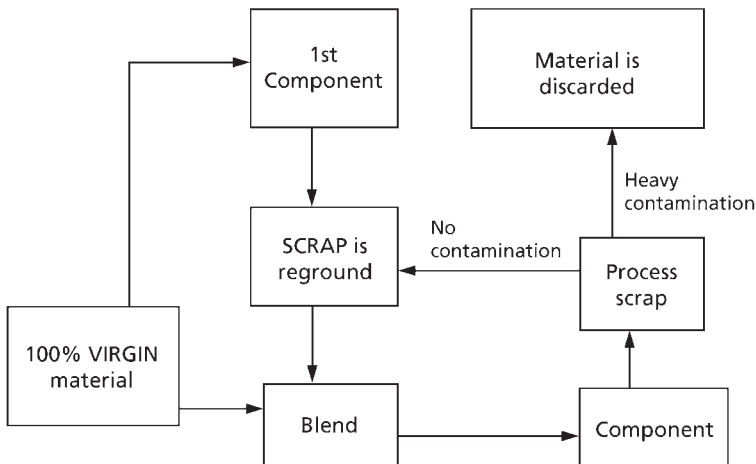
- i. Mould a blend of 50% virgin and 50% of the third pass material

- ii. Keep some mouldings back for evaluation
- iii. Blend 50% of this first blend with 50% virgin
- iv. Repeat for a number of passes, e.g., 5
- v. Carry out mechanical/rheological evaluation on the blend moulding samples 1-5
- vi. Examine the results

**Method 2: Cascading 100% regrind**

As an alternative to closed loop recycling, a cascading method can be employed.

In this method regrind from each component goes into the next one. This is represented in **Figure 3.4**. The difference between this and



**Figure 3.4** Reprocessing by the cascade method

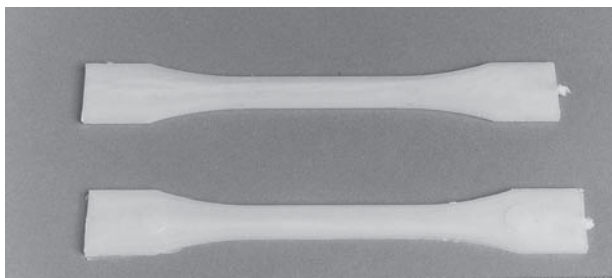
closed loop recycling such as described in methods 1A and 1B, is that here the regrind from each loop is used to make the subsequent component. This means that any heavily contaminated material can be discarded rather than being continually reprocessed.

### **3.5 Short-Term Mechanical Testing**

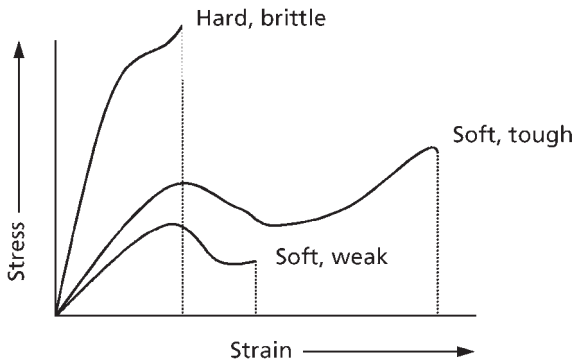
Experiments for measuring the effects of reprocessing have now been discussed. MFI as a method of monitoring degradation has already been mentioned, next the methods of mechanical evaluation will be considered namely tensile and impact properties.

#### **3.5.1 Tensile Testing**

Tensile testing can be thought of as a stretching test. Tensile properties are a method used widely to analyse the short-term stress-strain response of a material. Computer controlled tensile test machines are commonly employed, allowing one simple test to give a variety of information regarding strength, elongation and toughness. For this, a dumbbell-shaped test specimen is required such as the samples shown in **Figure 3.5**. Standard procedures are



**Figure 3.5** Standard tensile test pieces

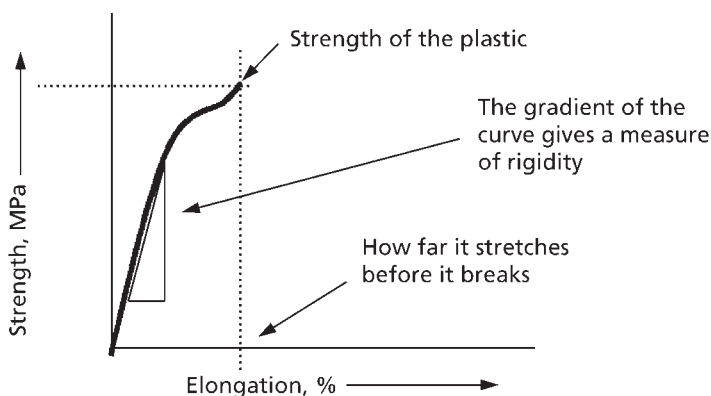


**Figure 3.6** Examples of stress-strain behaviour

used such as the International Organization for Standardisation method ISO 527 [3] or the American Society for Testing and Materials method, ASTM D638 [4] to ensure comparison can be made between materials. The shape and gradient of the curve produced describes the way the sample stretches or breaks, its strength and rigidity, and whether a material is brittle or ductile (pliant). Examples of such curves are given in **Figure 3.6**.

The way a stress-strain curve is used to determine mechanical property data is shown in **Figure 3.7**. This shows a stress-strain curve and indicates how values are obtained for:

- Tensile strength at break (the maximum stress).
- Elongation at break (the distance the material stretches (strained) before breaking).
- The rigidity of the material is calculated from the gradient of the curve. This value is sometimes shown as the tensile modulus.



**Figure 3.7** How mechanical properties are calculated from stress-strain data

Degradation of the plastic will cause the mechanical strength (stress in **Figure 3.6**) to drop, as well as causing premature failure of the material.

### **3.5.2 Impact Testing**

Impact tests measure the ability of a material to withstand a high velocity impact, for example, as might be experienced by a plastic kettle dropped from a kitchen worktop. Again, standard methods (e.g., ASTM D256 [5]) and specimens are employed, the results give a measure of the toughness of materials. Generally, the methods used fall into two categories. In one, a pendulum strikes a sample and the energy required to break the test piece in one pendulum swing is noted. This is most often seen on data sheets as Charpy or Izod impact tests. Both Charpy and Izod use a standard striking energy (see **Table 3.2**).

Table 3.2 Standard striking impact energies	
Impact test type	Striking energy (J)
Charpy	300
Izod	167
Drop test	Depends on height and weight

Samples can also be notched, the size and shape of the notch is also standardised. This ensures that the samples fracture.

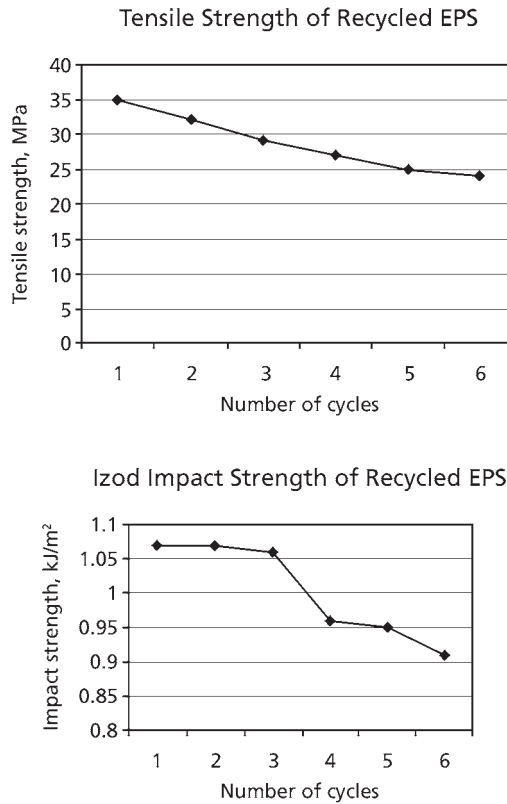
The second method involves dropping free falling weights onto samples. Free falling drop tests allow higher velocities and impact energies to be achieved. Useful data can also be gathered by doing impact tests at different temperatures as often this reflects more accurately the kind of environmental conditions the plastic will be subject to. For example, how a car bumper performs under impact at 25 °C may be different to how it performs at -10 °C. It may become more brittle at low temperatures. Whatever impact test method is employed, polymer degradation should, like tensile testing, show up as a reduction in the property measured.

### ***3.5.3 Tensile and Impact Testing of Recycled Expanded Polystyrene***

To show the kind of effects that are observed due to degradation, the following example shows the results of a study using Method 1A on recycled expanded polystyrene. This method is typically used for foam cups and packaging.

**Figure 3.8** clearly illustrates mechanical degradation as a result of reprocessing. The properties of recycle materials are

intrinsically linked to their processing history. Equipped with this knowledge, the stages of recycling are the focus of the next two chapters.



**Figure 3.8** Mechanical performance of EPS after repeated cycling by injection moulding [2]

## References

1. F.N. Cogswell, *Polymer Melt Rheology: A Guide for Industrial Practice*, Woodhead Publishing, Cambridge, UK, 1994.
2. D. Ciesielska and P. Liu in *Proceedings of Antec '98*, Atlanta, GA, USA, 1998, Volume III, p.2906.
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5. ASTM D257-06a, *Standard Test Methods for Determining the Izod Pendulum Impact Resistance of Plastics*, 2006.

## Suggested Further Reading

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7. A.N. Wilkinson and A.J. Ryan, *Polymer Processing and Structure Development*, Kluwer Academic, Dordrecht, The Netherlands, 1999.
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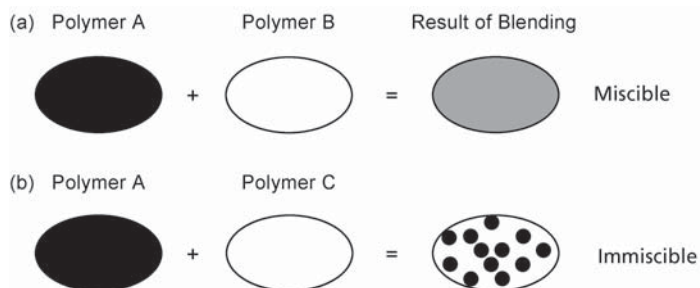
# 4 Why Plastics Need to be Sorted

We have already seen that thermosets cannot be reprocessed in the same manner as thermoplastics, because they do not re-melt. Therefore separation is needed of thermosets and thermoplastics. But what about thermoplastics: do they need to be separated from each other?

Can we simply just mix all the plastics together and reprocess them?

Well, if we could do this, plastics recycling would certainly be much easier. In some cases it may be possible to simply mix and reprocess but generally the properties of mixed plastics are not very good. Plastics tend not to be very compatible with each other, due to differences in their chemical compositions. The polymer molecules repel each other rather than mixing, much like a mixture of oil and water.

If two non-mixing polymers are put together, a process called phase separation occurs. A diagram of this system can be seen in **Figure 4.1(b)**; compare this with the miscible system in **Figure 4.1(a)**. Distinct regions of each polymer will be visible under a microscope or to the naked eye; no chemical bond exists between these materials. A way to imagine it is to think of an egg, where the yolk is inside but with no bond to the egg white. Now imagine an egg with lots of smaller yolks inside the white, this is what an immiscible polymer blend would look like. A commercial example of this kind of material is high impact polystyrene (HIPS). This is a blend of polystyrene and polybutadiene (a type of rubber).



**Figure 4.1** Blending miscible and immiscible polymers

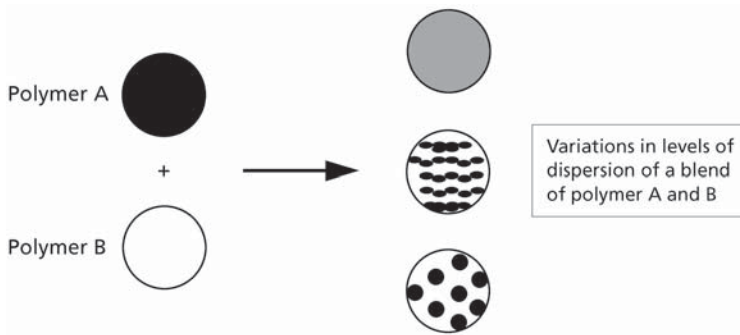
Polystyrene on its own is very brittle, whilst polybutadiene, as would be expected for a rubbery material, is a very good energy absorber and has the ability to bend instead of break. When these materials are blended, the result is a plastic which is much tougher than polystyrene alone.

One important point: the strength of these systems depend on how well one polymer is dispersed in the other. The better the materials can be dispersed, the better the properties of the blend will be. An additive called a compatibiliser can be used to assist one material to become very finely dispersed in the other. This will be discussed further in Chapter 7.

Tables, such as **Table 4.1**, are available to show how well polymers of different types mix. However, the general rule is that most are immiscible. The better the materials can be dispersed, the better the properties of the blend will be. Examples of various levels of dispersion are shown in **Figure 4.2**.

Thus, in order to reprocess recycle materials and retain good properties for a new product, we need well sorted materials rather than a blend of a number of immiscible plastics. A recycle

Table 4.1 Example of a miscibility guide								
Polymer	PS	PA	PC	PVC	PP	LDPE	HDPE	PET
Polystyrene	Y							
Polyamide	N	Y						
Polycarbonate	N	N	Y					
Polyvinyl chloride	N	N	N	Y				
Polypropylene	N	N	N	N	Y			
Low-density PE	N	N	N	N	N	Y		
High-density PE	N	N	N	N	N	Y	Y	
Polyethylene terephthalate	N	N	N	N	N	N	N	Y
<i>Y = miscible, N = immiscible</i>								



**Figure 4.2** Good dispersion (top right) and bad dispersion (bottom right)

material of high purity will also command a higher price in the market place, as it will be of better quality. However, this will be offset by the cost of sorting the plastic, for this reason methods are required to sort plastics as easily and economically as possible.

Many of the problems associated with the reprocessing of plastics have now been introduced. Before moving on to the processes of sorting and processing recycled plastic in more depth, a brief recap of the most important points will be given:

- The act of processing causes degradation of the material as a result of heat and shear.
- Mechanical actions such as grinding also exert shearing components.

There are problems associated with the processing of mixed plastics, these being:

- Plastics have different melting points and different temperatures for the onset of thermal degradation.
- The immiscibility of plastics with each other, leads to deterioration in mechanical performance.
- Good dispersion and homogeneity are required.

### **Suggested Further Reading**

1. S. Fuchs and M. Langr, Reprocessing of mixed plastics, *Kunststoffe Plast Europe*, 1995, 85, 1, 22.
2. H. Warth and D. Wittmann, Polymer blends, *Kunststoffe Plast Europe*, 1999, 89, 10, 39.

# 5 Reprocessing of Thermoplastic Recyclates

Mechanical recycling is the most common method of recycling. Here plastics are physically ground back to a suitable size (regrind) and reprocessed. The end use can be the original one or something different.

In the plastics industry it has long been common practice to reprocess waste material arising from normal production. This in-house recycling, known as primary recycling, makes economic sense as it reduces both production waste and utilisation of raw materials. For example, with injection moulding, regrind from start-up waste and production waste such as reject parts, can be fed directly back into the production machine.

For reclaiming used material or recycle outside of this scenario, the situation is slightly different and greater effort may be required on the part of the reprocessor. This type of mechanical recycling is termed secondary recycling (see **Table 5.1**).

Table 5.1 Types of mechanical recycling	
Primary Recycling	'In-house' reprocessing of production waste
Secondary Recycling	Mechanical recycling of single or mixed plastic materials from external sources

The material from external sources may be received in a variety of forms such as bales, mouldings or large lumps. It will probably need to be reduced in size, cleaned, separated and possibly recompounded and regranulated before it can be reprocessed in production. Often little is known about the history of the material to be recycled, for example:

- How many times it has been reprocessed previously?
- How much thermal degradation it has already undergone?
- Is it in-house or external waste?
- Is it a single material or a combination of plastics (commingled)?
- Is it contaminated or uncontaminated?
- What it was used for previously?
- Has it been damaged due to outdoor exposure, weathering, etc?

The characteristics of plastics can change depending on the exposure to thermal, mechanical (shear), oxidative and photochemical degradation processes. The characteristics of the recyclate may be quite different from those of the original virgin plastic.

Ideally, to produce high quality products, high quality materials are required. For this, consideration must be given to a number of factors. It must be determined as to whether the material is pure or commingled and whether it is contaminated, for example, with metal or wood. For ease of feeding into the processing machines be they injection moulding, extrusion or blow moulding, the size and shape of the regrind (i.e., the bulk density) must be suitable. If the material is hygroscopic (water absorbing), for example polyamide, it may require pre-drying. Finally, should the recyclate

be reprocessed on its own, mixed with other virgin material or modified with additives?

Within a closed loop cycle, it is easy to recycle materials and this is the reason that primary recycling is so commonplace. The key is having the knowledge of, and confidence in, the materials that are being used.

One example of a closed loop cycle in action is seen in the automotive industry. Since 1991 Volkswagen have recycled scrap bumpers made of a modified grade of polypropylene (PP). Their supplier reclaims the material, which is then mixed with virgin and returned to the bumper production process. The properties of the bumpers produced are as good as those made using virgin material alone. In tests it was found that no significant difference in characteristic properties occur until the material has been melted and extruded eight times [1].

It is easy to see the benefit of recycling in these closed loop environments. One of the biggest factors against the use of recyclate is the concern on the part of users that recyclate will reduce the quality of their product or damage their processing machinery. For this reason in the UK a number of groups such as Waste and Resources Action Program [2] (WRAP) and Consortium for Automotive Recycling [3] (CARE), have championed a recyclate materials standardisation programme. It is hoped that by providing a clear set of recyclate material properties, designers will be better positioned to specify, and have confidence in, recyclate materials.

The effects on material properties of mechanical recycling can be explored by repeated cycling of material through processing machines (see Section 3.4). Material from each cycling loop can be assessed. For example, in the production of the Volkswagen bumpers mentioned earlier, tests found that properties changed significantly, only after eight cycles of reprocessing. Experiments of this kind have shown that short-term properties do not vary

too greatly if the material does not contain glass fibres. Glass fibre is a very common reinforcement used in plastics. However, this material tends to become damaged when reprocessed. The mechanical strength of the plastic is dependent on the length of the fibres used and the act of processing reduces this residual length.

However, a word of caution should be applied here. Note that these are short-term properties only. The long-term effects of repeated processing on plastic properties are still under investigation. Whether these materials, when mixed with virgin, will undergo accelerated degradation is still the subject of current research. It does seem clear however, that incorrect processing parameters (too high temperatures) cause far more damage to the plastics than repeated processing at suitable temperatures.

One important criteria for high quality processing is the homogeneity of the material.

When recyclates are mixtures of different viscosity and colour, it is important that they are mixed adequately together to form one coherent material. Special screws are available for processing equipment. These homogenising screws improve both the product quality and the reproducibility.

Homogeneity is a word that you will encounter throughout this book. It is a most important concept, as much of the processing work done on a material is carried out to get it to a consistent state. This has a number of benefits:

- Highly automated machinery can be used in production with the knowledge that it will not need to be adjusted greatly.
- The properties and quality of the production component are known and will not vary drastically.
- Quality procedures are less time consuming and faults are easier to identify and trace.



- The customer will get a high quality product of consistent quality.

In fact, achieving homogeneity with recyclates, especially mixed materials, is difficult and sometimes impossible. The technology of reprocessing recycled plastics still has a way to develop. This means that quality control for recyclates is every bit as necessary as for virgin material.

For example, imagine you have a recycled material that was a 40% glass filled polypropylene with a data sheet of properties provided from the supplier of virgin material.

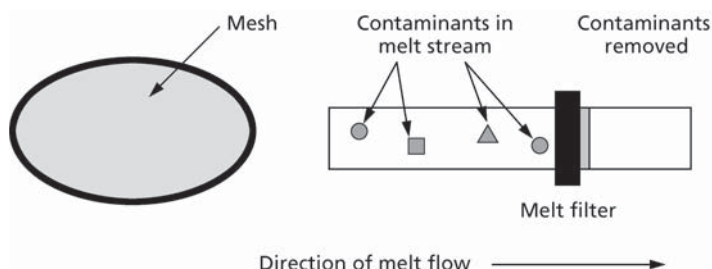
How will those properties have changed?

Is that datasheet a true reflection of the material you have in front of you?

Hopefully, having read Chapters 1-4, you will now be in a position to answer this question or, perhaps more specifically, to know which questions to ask!

## **5.1 Contaminants**

The reasons for the use of single polymer rather than commingled waste for production of quality parts were discussed in Chapter 3. As polymers are immiscible and mixing can cause mechanical property deterioration, so can contaminants such as paint or dirt. Contaminants can include paint, labels, coatings, dust, wood, metals, glue residues or printing inks. Metals are a particular problem in reprocessing as they can damage the internal workings of the processing machines. Protection from metal contamination normally takes the form of magnets situated in the feed hoppers, these are used even in the processing of virgin materials. Unfortunately, non-magnetic metals are not so easy to remove, and, if they cannot be



**Figure 5.1** Melt filter screen

removed by hand, will be fed through with the rest of the material. If the level of other contamination is low and the contaminants do not melt within the melting range of the polymer, they may be removed from the melt without too much difficulty using a filter screen. A filter screen looks like a very fine mesh sieve and traps larger particles, which are unable to pass through (Figure 5.1). They come in a variety of mesh sizes to suit the application and need. Screens need to be changed at regular intervals to prevent them from getting blocked. The frequency of changing will depend on the level of contamination. Filter devices of this type can be used on extrusion or injection moulding machines. However, only fairly low levels of contamination can be tolerated, usually 1% or less.

The use of screens is not confined to recycled materials, for example, manufacturers of highly pigmented polymers use screen packs to remove lumps of pigments that have not dispersed fully in the polymer mixture. Screen packs can be placed either in the die (extrusion) or nozzle (injection moulding), or in the melt stream. It is important that monitoring systems are available to indicate when the filter may need changing, since alterations in the process, especially in injection moulding, will change the quality of the mouldings produced.

If the screen pack becomes blocked, the pressure in the system will increase as the molten material will have a much narrower gap to flow through. This will also increase the shear on the material. Shear heating of the plastic may result, raising the temperature inside the barrel of the extruder or injection moulding machine. The effects of all these processes will be a change in the viscosity and flow properties of the material compared to when the screen pack is unblocked. With injection moulding this may necessitate a change in machine set up. Any moulding may therefore have different properties to those produced when the screen pack is relatively clear. Therefore it is very important to monitor changes.

Contaminants reduce the mechanical properties of components. Therefore filtration can improve properties. However, this can be offset by the increase in shearing associated with pressure build up in the melt behind the filter screens. Increased shear could cause degradation and reduce mechanical performance. Therefore, the size of the mesh must be selected to balance these two effects.

If contaminants melt during processing, there is no way to remove them and they will be homogenised within the melt during the processing stage. These contaminants may subsequently be visible in the component.

## **5.2 Recycling Techniques**

Despite increasing research efforts it is not yet economical to separate the wide variety of plastics that end up in the waste stream. The ideal is streams of single, clean and homogeneous recyclates, which present little technical effort for recycling. Of course, streams of this type, mainly industrial, can and are recycled. However, mixed waste streams present more of a technical and economic challenge to recover.

Consider your household rubbish, perhaps even rummage in your bin!

What plastics are present and what form are they in?

You are likely to find items such as packaging films, detergent bottles, carrier bags, milk bottles, food and household containers.

What possible contaminants are present?

You may have found food debris and residues from the various containers. You may also have noticed paper labels or glue residues or possibly even the use of other materials in combination with plastic, such as aluminium linings or metal closures. Now we have not only a mixed plastics waste stream, it is also contaminated with other materials.

What sort of plastics is the waste stream made up of?

You will find many packaging items are marked with an identification code like those shown in **Figure 5.2**.

The average breakdown of the composition of plastic components in a common household refuse collection is shown in **Table 5.2**.

Mixed plastic fractions reduce the quality of the products made from them quite considerably. This is due to differences in melting and processing temperatures and the lack of compatibility that was



**Figure 5.2** Society of Plastics Industry (SPI) packaging codes

Table 5.2 Mixed plastic fraction of household wastes	
Plastic	Fraction (approximately %)
Polyethylene	55
Polypropylene	15
Polyvinyl chloride	11
Polystyrene	9
Expanded polystyrene (foamed materials such as fast food packaging)	3
Remainder (various)	7

discussed more fully in Chapter 3. This, plus the contamination means that for quality plastics, the waste must undergo a sorting and cleaning process.

There are outlets for mixed plastics, but because of the heterogeneous composition of the raw materials they are limited to the production of large components. This is so that contaminants and any material that has not melted and mixed will not have a great effect on the overall strength. Often products of this type find outlets as plastic lumber or concrete replacement products such as park tables, slabs or benches, where the non-rotting properties of plastics can be utilised.

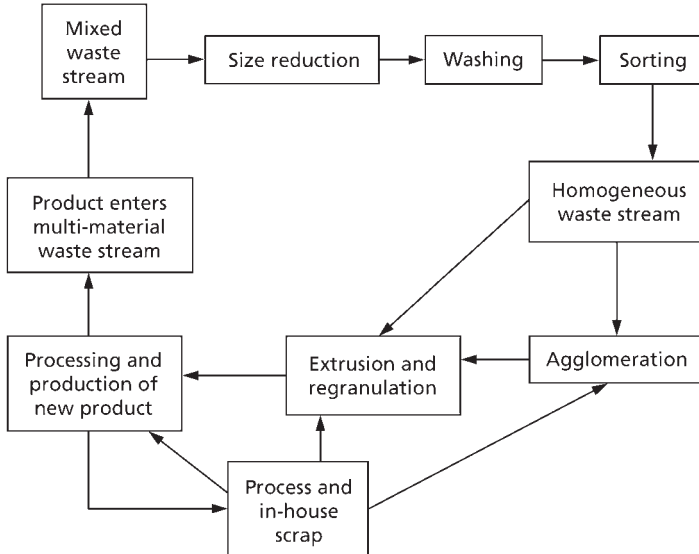
An example of a process for mixed plastic waste is that used by Wormser Kunststoff Recycling GmbH (WKR) in Germany. This process can tolerate a certain amount of contamination in the process mixture, which is appropriately treated in an extruder, and cast into large moulds to give products. Methods such as these will be discussed in Chapter 6.

Whether the material is reprocessed as a mixed waste stream or is sorted into separate fractions, it still needs to undergo some treatment. A typical recycling route for waste plastics can be split into two types of processes:

- (1) Physical/mechanical treatment to prepare and homogenise the waste, and
- (2) Melt processing.

Examples of stage one processes could include storage, size reduction, washing and sorting of the waste. Stage two would include regranulation and reprocessing.

An outline of the various stages of the waste cycle is shown in **Figure 5.3**. These will now be discussed.



**Figure 5.3** A process stream for recycled plastic material

### **5.3 Size Reduction**

Size reduction is necessary, because the material particles must be a suitable size for further processing. This may involve a two-stage process, the first using a shredder to produce large particles of about 25-50 mm. These materials can then be flaked. Rotary cutters are most commonly employed for the latter, as they can be used for comminuting (breaking down the size of) virtually any plastic. The rotary cutter is a fairly simple device consisting of the rotor and rotating knives, stationary (stator) knives, the grinding chamber and the screen. As the plastic moves between the stationary and rotating blades it is cut down to size. This size is determined by the mesh size of the screen, a common size is around 5 mm × 5 mm. A rotary cutter must be able to dissipate the heat generated from the shearing action of the blades. This can be done with an air extractor, which also aids in moving regrind material out of the chamber. Because contaminants may get into the system and because of the variable hardness and variety of plastics, the knives are mounted to attain the best cutting action possible. It is important as a design feature that the knives can be rapidly re-set, replaced or removed for resharpening as they are likely to undergo considerable wear.

### **5.4 Washing**

Washing is required to remove any dirt and residues adhering to the waste plastic. It increases the purity of the plastics and in some cases improves the efficiency of other processes such as sorting. The principles are the same as those applied to any household washing detergent. The contaminants must adhere more strongly to the cleaning medium than the plastic to allow for removal. Washing also removes labels and water soluble glue residues. Once the materials are washed they then need to be dried. This can be done mechanically simply using gravity and a conveyor to allow any liquid to drain away. Thermal methods use hot air to dry the plastic flakes.

## 5.5 Identification and Sorting of Plastics

One way to allow easy identification of plastics is to mark the mouldings. This is mandatory in the packaging industry, so turning over a plastic bottle or container should reveal a plastics identity code such as that shown in **Figure 5.2**. This allows the plastics to be sorted manually. Manual sorting is a very labour intensive process requiring little equipment, but relies on the accuracy of the human labour to produce a high purity product (**Figure 5.4**).



**Figure 5.4 Linesorting**

Clipart provided by RECOUP - promoting plastic bottle recycling

An alternative is to use mechanised sorting technologies. This works by utilising differences in material properties. For example, the densities of some common plastics are shown in **Table 5.3**.

The polyolefin fractions (PP, LDPE, HDPE) all have densities below  $1 \text{ g/cm}^3$ . This allows a process called 'float-and-sink' to be used to separate them from the other polymer fractions. Separation is carried out in a flotation tank using water as the separation medium.

Imagine you have a sack filled with bath sponges and house bricks and you were asked to separate them. Then imagine what would

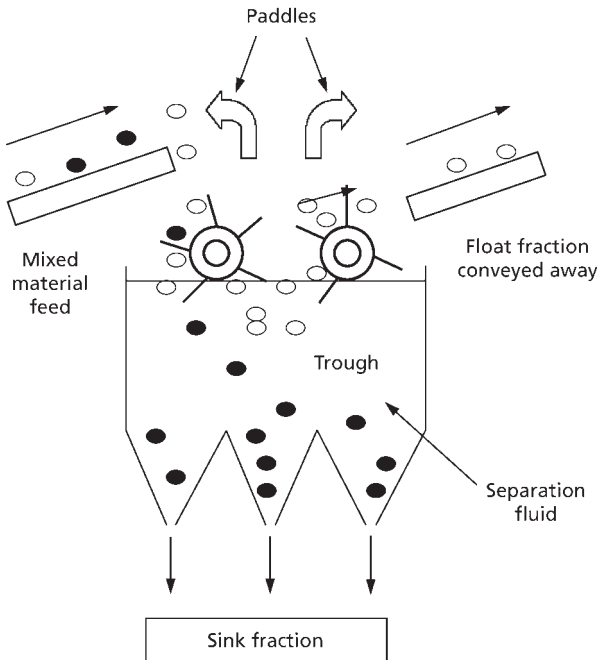


Table 5.3 Densities of common thermoplastics	
Plastic	Density (g/cm <sup>3</sup> )
Polypropylene	0.90
Low-density polyethylene (LDPE)	0.90
High-density polyethylene (HDPE)	0.95
Polystyrene	1.05
Polyamide (PA6 or PA66)	1.15
Polyvinyl chloride (PVC)	1.40
Polyethylene terephthalate (PET)	1.40

happen if you tipped this in a bath full of water. It would allow you to scoop the floating sponges, leaving all the house bricks at the bottom. The same principle applies in float-and-sink separators. As the name suggests, this density separation technique involves a floating fraction and a sinking fraction. The lighter polyolefin fraction remains floating on the surface and denser particles sink. A schematic of this process is shown in **Figure 5.5**.

Now look again at **Table 5.3**, PET and PVC have the same density. How can these materials be separated from each other? In this case a technique called X-ray fluorescence can be used. Many plastics are made up of the same elements such as carbon and hydrogen. PVC contains chlorine atoms. This technique detects the chlorine and can be used to indicate samples for removal from the waste stream. In this way PVC can be separated.

A further technique for separating generic material types is infra-red (IR) sorting. On exposure to IR light, the polymer molecules emit light energy, this can be detected and the spectral distribution that is produced is characteristic for each material type. For



**Figure 5.5** Float-and-sink separation

example a commercial IR machine operating in the near infra-red region may use a wavelength of 0.5 to 0.8  $\mu\text{m}$  to cause the emission of light in the plastic. Whilst in theory all types of plastic could be separated, in reality commercial machines tend to separate only popular generic types ie. PP, PA, polycarbonate, and polyurethanes. The base colour of plastics can also change the spectral pattern that is produced.

There are other techniques to separate plastics by colour, electrostatic charges and surface properties. The choice of sorting technique needs to take into account the likely composition of the plastic waste

and utilise the best and most economically available technology to attain end products of suitable purity for processing.

## **5.6 Agglomeration**

Agglomeration is a process stage to be carried out after the material is sorted into a fairly homogeneous stream. The aim of the agglomeration is to increase the bulk density of the waste, which is necessary to ensure good feeding for some plastication units. It finds most application in waste plastics with film flake, which can have a bulk density of just 100 to 150 kg/m<sup>3</sup>. This can make both feeding and storage cumbersome. Examples of film waste before and after agglomeration are shown in **Figure 5.6**.

Agglomeration can be differentiated from processing as here the aim is simply to bond the flakes together at their surfaces and therefore only the surfaces of the plastics are affected. Pressing or fusion are used for this, with the material being thermally stressed on the surface particles only for a relatively short time.



**Figure 5.6** Film waste before and after agglomeration

Thermal agglomeration is the method most widely practised with plastic wastes.

A number of stages to prepare wastes for processing have now been discussed. As it has been seen, preparing waste for processing can be time consuming and technically difficult. For this reason, most of the cost in reprocessing materials comes from these necessary, preprocessing stages. The next section looks at processing these materials to make new materials or new components. However, before that, an example of a successful closed loop recycling operation using some of the processes introduced here, is discussed.

In 2006, a scheme to collect HDPE milk bottles and recycle them into new milk bottles was trialled successfully in the UK. The recycle bottles were sourced both from bottles collected in curbside schemes and in 'bring in' bottle schemes. The bottles were washed in a 2% caustic solution at 93 °C to remove contaminants, labels and adhesive. Once dry, the sorting techniques used to identify the bottles were both IR detectors and sorting by hand in order to get a pure natural coloured recycle stream. This is used as a mixture of 30% recycle to 70% virgin plastic to make new milk bottles. Using plastic recycle materials in food contact also meant rigorous testing to ensure compliance with food packaging legislation. This is the first trial of what will hopefully become established practice in the future.

Recycling of HDPE bottles makes good business sense as it is a high volume material readily identifiable in the waste stream and collected curbside. For example, plastic bottle recycling in the US generated just under 1 billion kg of material in 2005 - 27.1% of this was HDPE.

## **References**

1. E. Burkle and P. Kalinger in *Recycling and Recovery of Plastics*, Eds., J. Brandrup, M. Bittner, G. Menges and W. Michaeli, Carl Hanser Verlag, Munich, Germany, 1996, p.350.
2. *Waste and Resources Action Programme (WRAP)*, [www.wrap.org.uk](http://www.wrap.org.uk), accessed September 2007
3. *Consortium for Automotive Recycling (CARE)*, [www.caregroup.org.uk](http://www.caregroup.org.uk), accessed September 2007.

## **Suggested Further Reading**

4. R.D. Pascoe, *Sorting of Waste Plastics for Recycling*, Rapra Review Reports, 2000, 11, 4.



# 6 Processing Techniques

In discussing processing techniques it is important to distinguish the type of waste we wish to process. A homogeneous waste stream can be reprocessed on the same machinery that virgin materials are processed on. A heterogeneous mixed plastic waste stream may also be processed, in some cases, on these machines, but a number of specialised reprocessing techniques may be applicable. A brief introduction to each of these processes will be provided along with examples of their use.

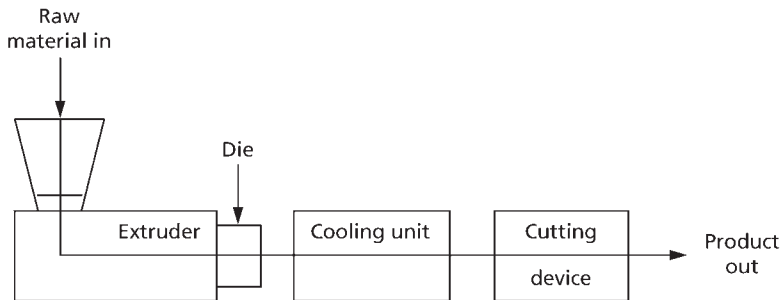
## 6.1 Extrusion

### 6.1.1 Introduction

Extrusion is a continuous process for the production of components such as pipes or sheets. It can also be used to produce compounds, which are mixtures of polymers or plastics and further additives. The most important features of an extrusion system are shown in **Figure 6.1**. These are:

#### *The Extruder*

Extruders can be of two types, i.e., single-screw or twin-screw machines. These two types of equipment perform slightly different tasks although the basic principles apply to both.



**Figure 6.1** Principle of extrusion

### *The Die*

This fits onto the end of an extruder and shapes the extrudate as it exits.

### *An External Cooling Unit*

This is required to cool the molten material and in its simplest form may be a bath either filled with or spraying water. Rollers are used to help feed the material to the cutting device.

### *A Cutting Device*

This is required to cut the extrudate to an appropriate size.

Whatever the end use destination is for a material, the chances are that at some point in its life it will have passed through an extruder. Extruders can be of two types, single-screw or twin-screw machines. These two types of equipment perform slightly different tasks although the basic principles apply to both. We will begin



with a discussion on extrusion compounding as this is of particular importance in the field of mechanical recycling.

### **6.1.2 Compounding**

We have already seen, in Chapter 2, that polymers are blended with a variety of fillers and additives to produce plastics. This conversion is carried out using an extruder to do the compounding.

The term compounding encompasses a variety of steps between the synthesis of the polymer and its final forming in a process machine. This could include feeding or conveying the material into a machine, metering the correct quantity and mixing the polymer with other materials such as additives. Finally, this would include pelletising the final plastic material, for example, for use as feedstock for injection moulding or blow moulding machines. The compounding route is outlined in **Figure 6.2**.

Metering	Feeding or conveying	Cold or hot mixing	Plastication	Pelletising
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**Figure 6.2** The plastic compounding route

In **Figure 6.2**, a five step compounding route was illustrated. This will now be described in greater detail.

#### ***Feeding, Conveying and Metering***

Generally, mechanical conveyors such as fed screws, conveyor belts or vibrating shutters are utilised. Larger operations may

employ pressure or vacuum operated silos to deliver material to the extruder or mixing stations. Accurate metering is required in many cases and gravimetric or volumetric type feeders can achieve this. Of these, gravimetric systems lend themselves to automation, having higher accuracy but a higher price. Once the required compound ingredients are metered, they need to be mixed.

### *Mixing*

The aim of mixing is to disperse the ingredients to produce a homogeneous mixture. This can be done at room temperature by simply tumble blending to produce a dry blend. Alternatively, the ingredients can be hot mixed. Generally hot mixers are situated directly above the extruder so that the melted mixture can be poured directly into the extruder.

### *Plastication*

This is necessary in order to mix and melt the material to produce a mixture that is both homogeneous and formable. This work is done by the extruder screw.

### *Cutting Devices*

The cutting device used will depend on the product. Pipes, sheets and profiles need to be cut into specific lengths using a saw. Rotary pelletisers, also known as strand cutters, are used to produce pellets.

An extruder screw functions as a feeder, a conveyor and a mixer. The screw must take plastic granules and melt and mix them, before the material is conveyed out through the die. Different screw

configurations and geometries are available, to make the screws more conveying or more plasticating as required for a particular application. Screw characterisation usually takes the form of an L/D ratio, where L is the length of a screw and D is the diameter. For example, a screw characterised as a 40 mm/20D, would have a screw diameter of 40 mm and a screw length of  $40 \times 20 = 800$  mm. A common screw length is 25D.

Generally, screws are designed with three specific zones: a feed zone, a compression zone and a metering zones. This ensures that the material is fed and conveyed, plasticated and homogenised. Further sections can be added to give additional mixing and shearing as required. Screws are tailored to particular materials and processes. General purpose screws are available that can process a range of materials. However, it is important that the screw used is suitable for each application.

Whilst this section is concerned with extrusion, other processes such as injection moulding, blow moulding and film blowing, all incorporate extruders in their design and the screws used for each are again tailored to the specific requirements of the process.

Material exits the extruder through a die. It is the die that forms and shapes the final product. By varying the die design a number of different products can be produced, such as pipes (for drainage, plumbing, etc.), sheets (for processes such as thermoforming, which will be discussed later in the chapter), profiles and sections (for window frames), or strands to be chopped into pellets for further processing. Once the material has passed through the die it must be cooled. Cooling units for profiles and pipes may also contain calibration units to give accurate sizing of the products. For pellets a simple water trough is sufficient. Profiles and pipes may utilise a haul-off system with a cutting device to cut the plastic into lengths. A blowing unit may be incorporated to dry the material before it enters the cutting units.

### **6.1.3 Single-Screw Extruders**

As the name suggests, the single-screw extruder has a single Archimedian screw that rotates in a heated metal barrel. Unlike twin-screw machines, which require material to be dosed into the screw to prevent an overload, solid material enters the barrel through a gravity feed hopper at the feed throat. This material is conveyed along the extruder barrel by the action of the screw. The material is plasticated during this action and then passes through a breaker plate before exiting at the die. A breaker plate is used to take the rotation out of the melt. Without a breaker plate, the material would spiral out of the die in line with the movement of the screw. It also helps to build up pressure in the melt. A breaker plate is illustrated in **Figure 6.3**. As the die also acts as a flow restricter, pressure is required to force the melt through. This is referred to as die head pressure and varies according to the size of the die and the speed and flow properties of the melt. The layout of an extruder is given in **Figure 6.4**.



**Figure 6.3** Breaker plate

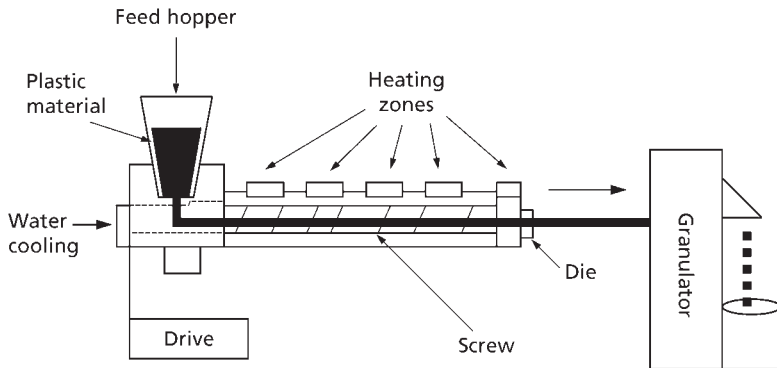


Figure 6.4 Schematic of an extruder

#### 6.1.4 Twin-Screw Extruders

A twin-screw extruder can have either counter-rotating or co-rotating screws. Co-rotating twin-screw extruders are used mainly for compounding. Counter-rotating screws are generally used in the processing of heat sensitive materials, such as polyvinylchloride (PVC) pipes and sheets. They are especially suited to heat sensitive materials, because they allow greater temperature control.

The aim of both types of screw is plastication, that is, to produce an easily formable melt stream. The temperature of extrusion will fall between the melting point of the polymer as a minimum, otherwise the polymer simply will not flow, but below the onset of thermal degradation to prevent excessive damage to the compound. The heating of the material is carried out by means of external heating zones, which are incorporated into the body of the machine. The number of zones will depend on the size of the extruder, generally they are positioned at the point of input, the centre region of the screw and the point of output. These correspond to the conveying section, the transition (melting) region and metering section, and

finally the exit die region. This allows the temperature to be varied across the length of the screw. Generally, the temperatures will be profiled, to be coolest at the point of input to aid with material feed, and hottest at the point of exit. The latter is to compensate for the extra heat that will be lost from the material in this region. The twin-screw is a very effective mixer and also ensures both an evenly dispersed mixture and an even temperature across the exiting material.

Because of the combination of feeding and screw action, twin-screw extruders can produce compounds with very low levels of polymers, in some cases less than 20%. The single-screw extruder cannot cope with such high levels of non-polymeric materials. However, for melt blending of virgin and recyclates or adding relatively low levels of additives the single-screw extruder is an effective method for mixing and compounding a plastic mixture.

Both single- and twin-screw extruders can be configured for particular polymeric materials. This can include the design of the screw to control levels of mixing, the use of vents to aid in removing volatiles or, in the case of twin-screws, additional feeding units can be incorporated downstream of the polymer feed. Extruders can also be used to make finished or semi-finished goods such as solid profiles (bars), hollow profiles (window frames), pipes, films, sheets and filaments, as discussed earlier. If the product is a granular material, it will find use as feedstock for other processes, for example, injection moulding or blow moulding.

### **6.1.5 Co-Extrusion**

For some applications, two different materials with differing properties are used together. Co-extrusion may be carried out to produce the component. Each material requires an individual extruder which feeds into a special co-extrusion die where the melts can be

combined as required. Multi-layer pipes and sheets can be produced, which enables recyclate materials to be sandwiched between virgin material outer layers if required. Multi-layer technologies are not limited to extrusion, it is also possible to create multi-layers using injection moulding, blow moulding and film blowing.

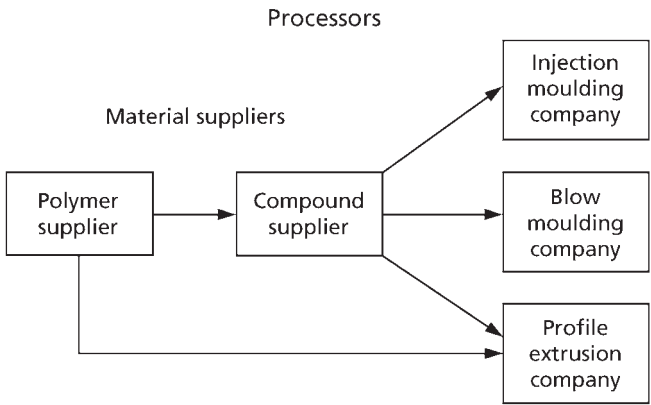
## **6.2 Supply Chains for Compounds**

The plastic material suppliers often carry out compounding. They will receive a quantity of virgin base polymer, such as polypropylene, from a polymer manufacturer and create a number of different formulations and grades for sales to their customers, who will require materials that can meet the specific needs of their end use applications. For example, simply by adding pigments, they can create a range of colours. In some cases this process might be continuous: instead of pelletising, the result may be an extruded product such as pipe.

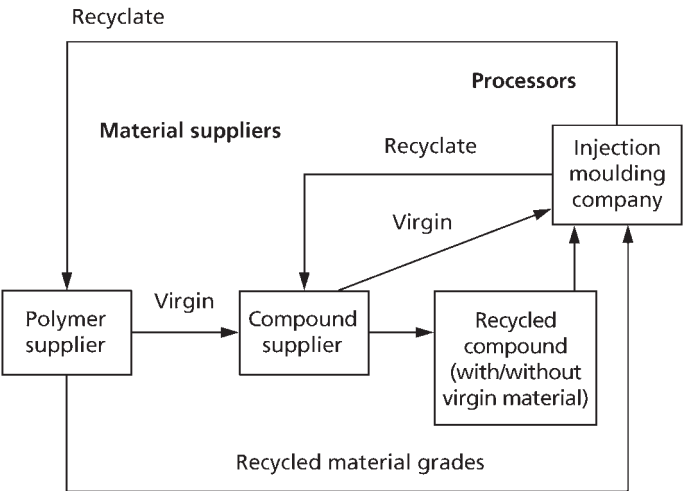
In considering the thermal history of plastics, most material will already have passed through some kind of a processing cycle before it even goes to the final manufacturer to make saleable production components. Examples of possible supply chains are shown in **Figure 6.5**.

When considering recycling of these materials, a similar supply chain may operate. Recyclate materials may be utilised by either the polymer supplier or the compound supplier to produce grades containing all recyclate, a mixture of recyclate and additives, or a mixture of recyclate and virgin material. Additives for recyclates will be discussed in greater detail in Chapter 7. A possible supply chain for recyclates is shown in **Figure 6.6**.

Processors may also perform compounding themselves, to customise materials for their own specific requirements. This may



**Figure 6.5** Supply chain from virgin polymer through to plastic component manufacture



**Figure 6.6** Supply chain for recycled materials



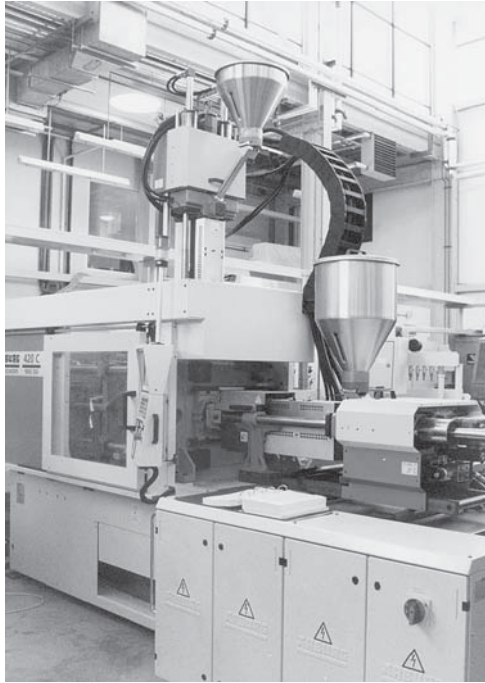
include the addition of colourants, regrind materials or other processing aids as required. Often additives and colorants are purchased as masterbatches.

Masterbatches are concentrated mixtures of colours and/or additives incorporated into suitable carrier materials. This enables easy incorporation of the selected masterbatch formulation into the production process. Often, masterbatches are used to improve the downtime when changing colour and materials, which improves production efficiency. It is more expensive to buy a masterbatch than an additive. However, the advantages, especially in cases where numerous colour changes are required, can quickly repay the cost. For example, carbon black pigment is very fine and incredibly difficult to remove from feed hoppers and mixers (and the production workers!), whereas a black masterbatch containing perhaps 20% black pigment in a carrier material such as low-density polyethylene (LDPE) can be added to the mixture at 1-5%, leaving the hoppers and mixers easy to clean, ready for the next blend.

Whether an additive is used in concentrated masterbatch form or in its standard form will vary depending on the requirements of particular producers. Masterbatches are routinely used for blow moulding and film blowing in commodity plastics such as polypropylene (PP), LDPE and high-density polyethylene (HDPE).

### **6.3 Injection Moulding**

Injection moulding is one of the most common manufacturing processes in use today. It lends itself to high volume production of both complex and precision parts with a variety of uses. It is a highly versatile process that is as successful and economic for both small and large components from an automotive bumper to intricate wristwatch parts.



**Figure 6.7** Injection moulding machine

An injection moulding machine consists of an injection unit and a mould clamping unit and is shown in **Figure 6.7**. The injection unit must convey, plasticate, mix and homogenise the melt. It must also be able to inject a fixed weight into the mould. This is called the shot weight and will vary depending on the shape and size of the component to be moulded. The clamping unit is responsible for opening and closing the mould as well as part ejection after moulding. The clamping mechanism applies a clamping force on the mould, to hold it together whilst the plastic material is injected.

A simple description of an injection moulding cycle is:

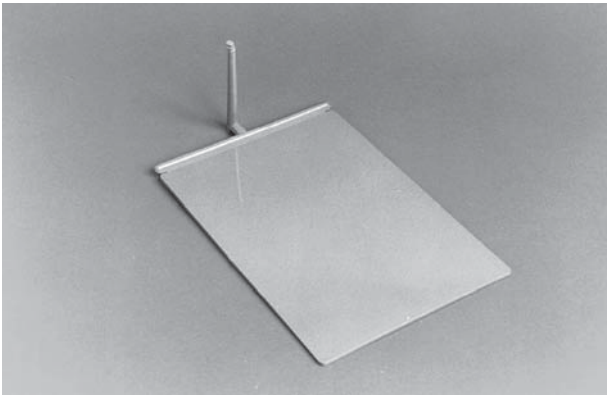
1. The mould closes,
2. Material is injected,
3. The material cools in the mould,
4. The injection unit meters the next shot,
5. The mould opens and the part is ejected.

Like an extruder, an injection moulding machine uses a screw to feed and plasticate the melt. There are however, a number of design differences between the two. An injection screw must withstand both higher pressures and intermittent stop-start use. It must be able to inject as well as move back to prepare the next weight of shot.

### ***6.3.1 Waste During the Injection Moulding Process***

As well as reject injection mouldings, waste is also generated through runners or sprue as shown in **Figure 6.8**. These are produced on each moulding and are the channels used to feed molten plastic from the injection unit into the mould. These, as well as reject mouldings, can be fed back into the machine if care is taken to avoid contamination. For this, slow-running, largely dust-free granulators are available, which can be quickly and easily cleaned as required.

Injection moulding is complex and controlled by a number of parameters. A range of materials and material viscosities can be utilised, however mixtures of plastics, if not homogeneous, can cause fluctuations in the process and make mouldings of consistent quality difficult to achieve. Although the screw of an injection moulding machine has many extruder like elements and shear mixing can be used to mix the melt prior to moulding, often recycle materials are blended, extruded and re-granulated prior to undergoing injection moulding.

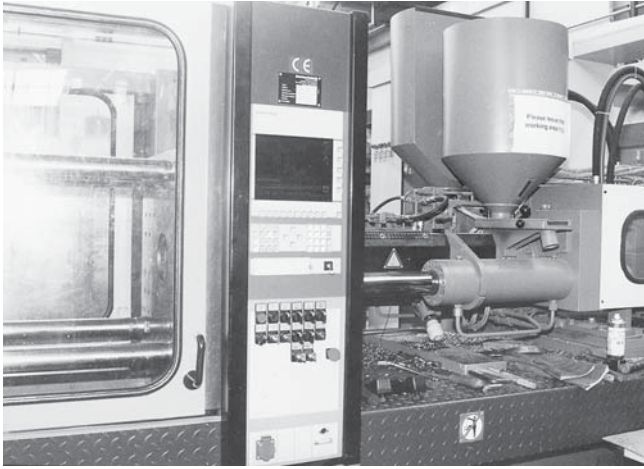


**Figure 6.8** A flat plaque moulding with the sprue waste still attached

If mixtures of materials with different melting points are used there can be problems, unless the temperature of the highest melting fraction is reached. Unmelted material will be visible in the mouldings, severely affecting the mechanical integrity. Likewise contaminants such as dirt, wood and other residues will also be visible in the mouldings. Melt filters can be used to trap relatively minor contaminants that do not melt and prevent them getting into the mouldings. One way to prevent this type of visible contamination is to use co-injection moulding.

### **6.3.2 Co-Injection Moulding**

There are a number of variations of the injection moulding process, one that is particularly applicable to recyclates is co-injection moulding. Co-injection moulding produces a sandwich like structure that can be used to encapsulate recyclate materials, covering them in a layer of virgin skin material.



**Figure 6.9** Co-injection moulding machine



**Figure 6.10** Skin/core configuration of co-injection moulding

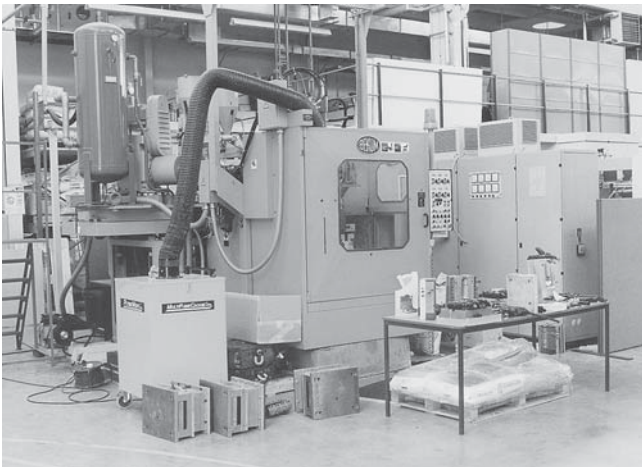
A co-injection moulding machine has two injection barrels feeding into a common die. A machine is shown in **Figure 6.9**. The recyclate materials that make up the core can be contaminated or mixed plastics whilst the surface skin, which can be seen, is made up of 100% virgin material. The process works better if the core is more viscous than the skin. **Figure 6.10** shows what the skin-core configuration would look like, if the skin were

transparent and the core black. Of course, generally, the core would be hidden from view by the skin material. If the rheology of the skin and core is optimised, it may be possible to hide up to 70% of a recycle in this way.

## **6.4 Blow Moulding**

Blow moulding is the third most commercially important process for plastics production after extrusion and injection moulding. It is used to produce a range of hollow articles, for example, bottles, fuel tanks and other large containers. There are two main variations, injection blow moulding and extrusion blow moulding. The process sequence for both is the same.

- The material is either extruded or injected to produce a tube like preform.



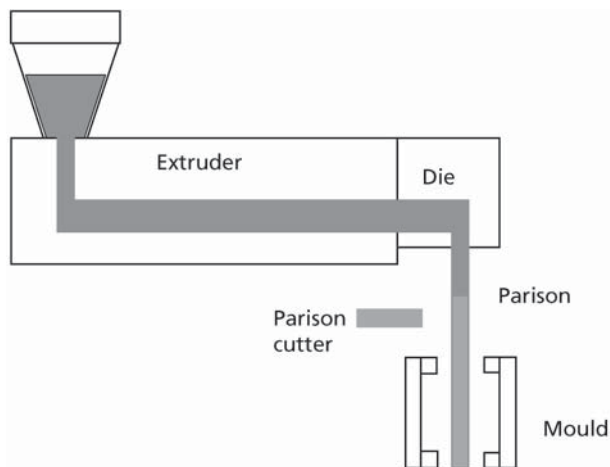
**Figure 6.11** Blow moulding machines

- The preform is blown out to the shape of the mould and then cooled.

Injection blow moulding is most commonly employed for the production of transparent soft drinks containers. However, extrusion blow moulding is the method most commonly employed for mouldings such as shampoo and detergent containers, plastic drums and milk bottles. An extrusion blow moulding machine is shown in **Figure 6.11**.

#### **6.4.1 Extrusion Blow Moulding**

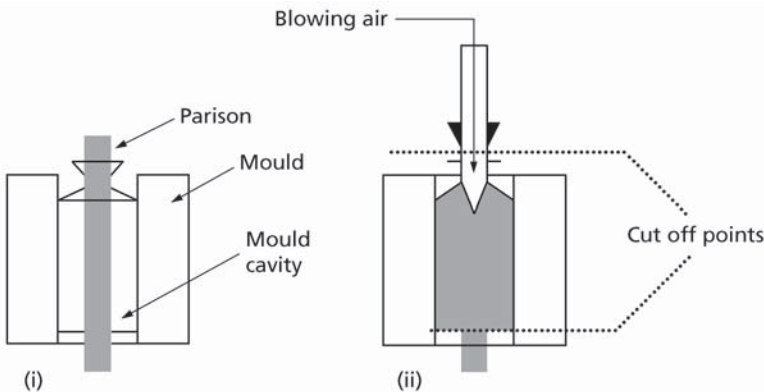
The material is fed through a transfer screw into a die head, where the material is melted and passes out through a die as a tube-like extrudate termed a parison. This is illustrated in **Figure 6.12**. This process can be either continuous or, with larger articles, intermittent.



**Figure 6.12** Extrusion blow moulding. Step 1: Parison formation

The parison extrudes down vertically and the process relies on the hot strength of the plastic to hold the parison weight in shape. For this reason blow moulding uses far more viscous materials than would normally be employed for the injection moulding process. A low viscosity material would simply pour out of the die onto the floor or split off before the parison had formed.

The parison will continue to extrude until it reaches the base of the mould. At this point the mould will close and the parison will be cut above the mould with a hot knife. The mould is now moved away from the parison, taking the cut off slice of parison closed in the mould with it. The next parison continues to extrude. The inflation of the parison can now commence. A blow pin comes down into the top of the mould and blows air in to inflate the hot parison against the sides of the mould (**Figure 6.13**). The mould is cooled with water: this aids heat removal to help solidify the newly formed article. The blow pin is removed and the tool opens to eject the part. The mould can then return to collect the next parison and start a new moulding cycle.



**Figure 6.13** Extrusion blow moulding. Step 2: Parison inflation.  
(i) Parison in relation to closed mould (ii) inflated parison



It can be seen in **Figure 6.13**, that the parison exceeds the required length of the part. This excess material is produced as scrap on each moulding. The formation and removal of scrap is indicated in **Figure 6.13(ii)**. The material discarded at the bottom is termed the 'pinch off' due to the fact that the lower end of the material is pinched off and sealed in the mould to form the base. The top scrap is termed 'neck flash' and is removed by a cutting device incorporated into the blowing pin, which matches the cutting region on the mould. Providing that the scrap from both the top and bottom is kept clean, it can be reground and returned to the production process. 100% regrind can be reused if required. Generally, however, it would be blended with virgin material. Recyclates coming from other waste streams are more difficult to process due to the problems of contamination. The criteria for a blow moulding material are quite specific:

- It must be of suitable viscosity.
- It must have high melt strength.
- It must be extendable when inflating (this is often given as an the inflation ratio for the material).
- It must be able to seal at the base of the moulding.

As well as the possible effects of contaminants on viscosity, they can also cause problems with the inflation process. During inflation the material expands at a constant rate to give a constant wall thickness across the body of the moulding. Contaminants can cause bursting, tearing or affect the ability of the parison to seal at the base. Finally, there is the colour limitation of reprocessing materials, especially mixtures of different colours. Often to get a uniform colour, a black masterbatch is added to mask the underlying colours of the recyclates. This can limit potential outlets for products. However, one solution to overcome this is to use more than one extruder to produce a multi-layer parison. This process is called multi-layer extrusion blow moulding.

**Multi-Layer Structures**

Multi-layer blow mouldings, give the process added versatility by allowing the use of layers of different materials that can be tailored for purpose and economy. Multi-layers also provide a means of incorporating recyclates and masking the inherent colour of the recycle itself. For example, consider a two-layer bottle structure that used blue virgin material as the outer visible layer and black recycle as the inner layer. If you actually looked into the bottle you would see the black recycle material, but all of the outer surface would be blue.

Possible layer configurations are shown in **Figure 6.14**. A 3-layer configuration for recyclates may be preferable to 2-layers as the inner layer primarily affects the strength of the weld line on the base of the moulding. This seam can be potentially weakened with recycle. There is another potential problem with a 2-layer configuration: the recycle may not be a suitable material to come into contact with the contents of the container. This could be either due to chemical compatibility problems or simply that the surface finish on the recycle material would not be of a high



**Figure 6.14** Examples of multi-layer structures for blow mouldings

enough quality for the desired product. A 3-layer configuration overcomes this. Blow moulding machines allow accurate control of thickness of the individual layers, so that the level of each of the layers can be optimised. Generally the inner and outer layer would take up 10-20% of the overall thickness with the rest made up of recycle material.

Some applications may require the use of an additional barrier layer, for example, fuel tanks require a fuel impermeable barrier, and food containers such as tomato ketchup may require a barrier to prevent odours penetrating through the outer layers. The simplest barrier configuration incorporating recycle is a 4-layer structure as illustrated in **Figure 6.14**. The adhesive layer is needed to bond the layers together as often the required material combinations do not stick to one another. The adhesive layer, sometimes termed the tie layer, ensures a good bond is formed.

Any recycle derived from multi-layer mouldings will consist of a combination of the materials used to make up the individual layers. This does not usually present a problem as the layers are all of suitable properties for blow moulding and compatibilised with each other.

The incorporation of scrap into extrusion blow mouldings from extrusion blow mouldings does not present a problem. However, given the specific requirements of the blow moulding process in terms of viscosity, melt strength and inflation properties, materials from other waste streams are unlikely to be suitable. The blow moulding process is relatively intolerant to contaminants due to the effects on the ability to inflate the parison and the evenness of the wall thickness that is produced. If using recycles, special attention must be paid to the pinch-off area in the seam to ensure adequate weld strength is produced. Weld strength will be discussed in Section 6.5.

### **6.4.2 Injection Blow Moulding**

Injection and extrusion blow moulding take their names from the methods used to produce the tube for blowing. In extrusion blow moulding the tube is called the parison, in the case of injection blow moulding it is termed a preform. Thus in injection blow moulding, injection moulding is used to produce the preform.

The process sequence for injection blow moulding is as follows:

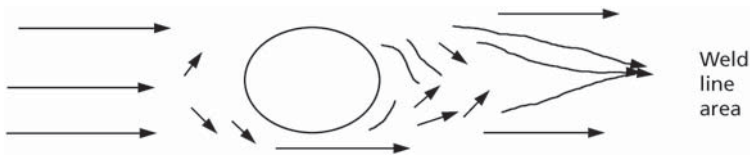
- The preform is injection moulded.
- It is transferred to a blowing station and inflated inside a mould.
- It is transferred to a station where it is stripped from the mould.

The process thereby uses two moulds, one for injection and one for blowing. There are several advantages to injection blow moulding. From a waste management point of view the major advantage over extrusion blow moulding is that no trim scrap is produced during moulding. By injection moulding the preform, accurate control can be maintained on both the neck moulding and the preform itself, in terms of dimensional accuracy and wall thickness. However, only simple shapes can be produced, unlike in extrusion blow moulding where handles can be incorporated into the moulding. Generally, injection blow moulding makes use of PET, PVC and PP. Bottles produced by this method can be recognised by a mark on the base of the moulding, which shows the injection point of molten material into the injection moulding tool, from injection moulding of the preform.

Like extrusion blow moulding, injection blow moulding places very specific demands on the raw material it uses and is intolerant to contaminants. Regrind from inhouse waste may be utilised providing attention is paid to cleanliness.

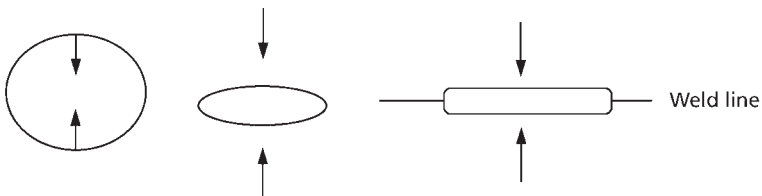
## 6.5 Weld Lines

Whenever molten flows come together a weld line will be produced. Weld lines are common to almost all processing operations as often on passing through extruders or moulds (extruder dies, injection moulding tools, blow moulding tools), molten flows will meet obstructions which split material into different streams, this is shown in **Figure 6.15**. How well the materials can ‘knit’ back together, will affect the weld line strength.

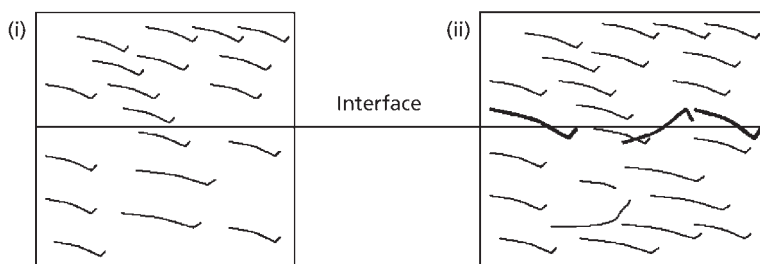


**Figure 6.15** Molten material flowing around obstruction

In extrusion blow moulding of bottles, for the bottle to be sealed the parison must weld at the seam. The parison is pressed together by the blow moulding tool, creating a weld line as shown in **Figure 6.16**.



**Figure 6.16** Cross-section of a parison as it is welded to form the base seal

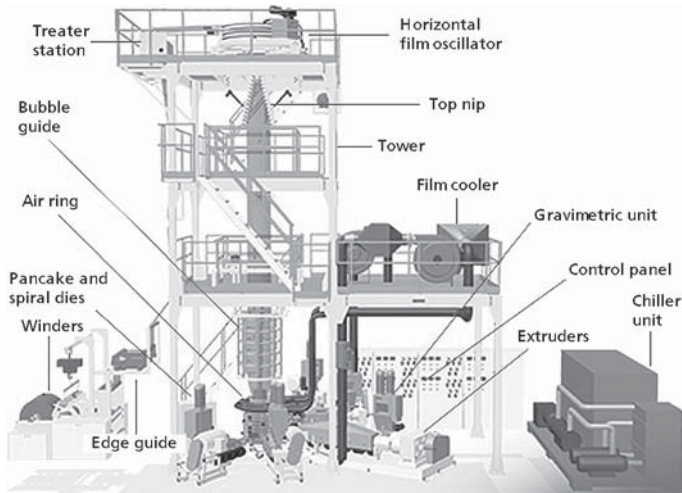


**Figure 6.17** Weld lines showing (i) no entanglements and (ii) chain entanglements

The strength at the weld will depend on how well the material can knit across the interface. In **Figure 6.17**, two possible outcomes are shown. On the right, polymer chains (indicated in bold), are able to cross over the interface forming a bond between both sides of the blown parison. To do this the polymer needs to be in the molten state: if the material solidifies, chains cannot pass from one side of the interface to the other. The left-hand diagram shows no chain entanglements at the interface and therefore there is no bond between these two plastic sections. The number of entanglements will be related to the weld line strength, the more entanglements there are the higher the strength will be. The weld line strength depends on: the contact time of the molten material, the material temperature, the cooling rate and the properties of particular materials. Materials vary in their ability to form strong weld lines. Changing the properties of a material by reprocessing may also affect weld line characteristics.

## 6.6 Film Blowing

A schematic of the film blowing process is given in **Figure 6.18**. The plastic material is fed through an extruder to an annular die opening.



**Figure 6.18** The film blowing process  
(*Courtesy of Alpha Marathon Technologies Inc.*)

The cylindrical molten tube is inflated from the inside by blowing air, creating a bubble of material that can be fed and collected onto rollers. Cooling is achieved by blowing air through a cooling ring situated above the die.

Process waste is not generated in great quantities once the machine is running and material can be reprocessed providing that it stays free from contamination. Like blow moulding, large occlusions or contaminants in the process can cause bursting and inflation problems. Agglomeration may be necessary to aid feeding in some cases, due to the low bulk densities of shredded films.

Large amounts of film scrap are available, because of the short lifetime associated with packaging and industrial film materials such as carrier bags, dustbin liners and plastic sacks. A typical lifetime of products of this type is only two years.

100% recyclate material may be used in low-grade applications such as bin liners. Other products such as carrier bags may incorporate scrap in with the virgin material to reduce cost.

Again, like blow moulding, film blowing has specific material requirements in terms of melt strength, viscosity and inflation characteristics. Generally film blowing is limited to polyolefin materials, the majority of usage being of LDPE, LLDPE and HDPE.

## **6.7 Compression Moulding**

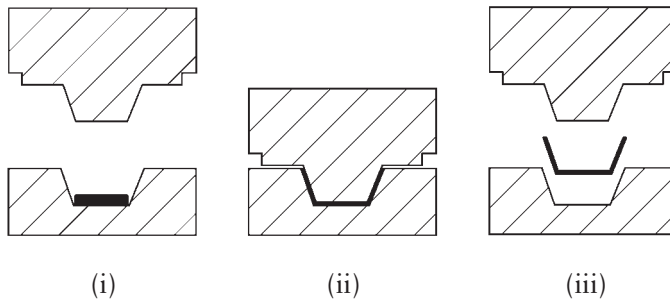
Compression moulding is used to manufacture both thermoplastic and thermoset products. The process sequence is:

- The moulding compound is loaded.
- The mould is closed.
- The compression force and the heat of the mould cause flow.
- The mould opens.
- The part is ejected.

All the processes up to now have used materials in granular form, compression moulding however, often utilises raw materials in sheet form. Sections called blanks, of the correct weight, are pre-heated and then placed in the compression moulding tool. This is then closed to form the component. Because of the use of sheets rather than granules the raw material costs are much higher, as it is more expensive to manufacture sheets than granules. One common type of sheet is known as glass mat transfer (GMT); it consists of polypropylene and high levels of glass fibre. The sequence of moulding is shown in **Figure 6.19**.

Any recyclate can be used to make further GMT sheets. However the glass levels and flow characteristics of the sheet may be





**Figure 6.19** Compression moulding. (i) Blank placed in (ii) Tool closed, mould, blank compressed (iii) Part ejection

different. As these are generally provided for the manufacturers by a supplier, recycling of GMT by the compression moulders themselves is not common.

Compression moulding of mixed plastics is possible. Pre-melting materials into a suitable weighted 'blank' and placing it into the mould is necessary. Moulding is then carried out in a normal way. Thick sections can be made in this way, however they do not have very good properties for the reasons discussed in Chapter 4.

## **6.8 Thermoforming**

Like compression moulding, thermoforming uses sheet rather than granules. In this process the sheets are clamped onto a frame and then heated to soften, but not melt, the plastic. A mould is then brought into contact with the sheet whilst a vacuum is applied. This draws the sheet onto the surface of the mould and forms the moulding. The moulding must be trimmed to remove the excess sheet material. This scrap can be returned to the sheet supplier to be used in the production of new sheet.

Polystyrene foam and polyethylene are commonly used in thermoforming. Both of these materials are used to produce packaging, such as fast-food boxes, pots and dishes. Drink dispenser cups are also commonly produced by thermoforming.

## **6.9 Processes for Incorporating Mixed Plastic Waste**

The next three processes are suitable for mixed and more contaminated waste streams. There are commercial operations of each of these processes, variations occur depending on the type of waste being processed. Only an overview of each general process is presented here.

### **6.9.1 Intrusion Moulding**

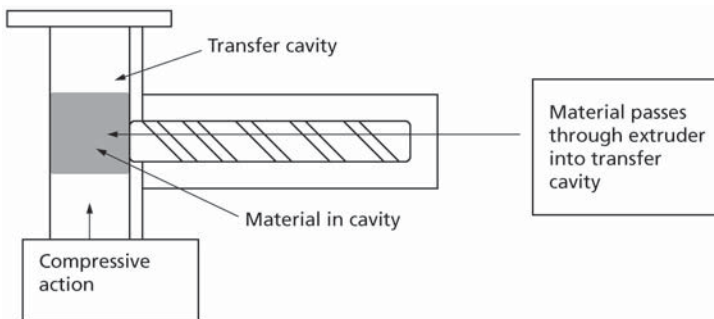
The intrusion process is suited to mixed plastics. Generally, they are finely ground before processing to aid dispersion. The process has elements of extrusion in that a plasticating unit is used to soften the mixture, which is then fed into a mould and this is then cooled. On rotating systems a number of tools can be filled as others are cooled (usually by submerging them in water). Once the plastic has cooled it can be ejected or removed depending on the type of mould that is used. The process is tolerant to contaminants such as mixed plastics, sand, glass, wood and paper, providing a minimum polyolefin fraction of around 40% is present [1]. Other contaminants become embedded in this low melting fraction. This process is generally used to produce large, geometrically simple shapes such as profiles and panels for wood replacement applications such as fencing, posts and scaffolding.

### **6.9.2 Transfer Moulding**

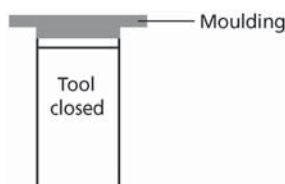
This process combines elements of injection moulding and compression moulding. It is similar to injection moulding in that

a fixed weight of material is transferred into a mould. Transfer moulding was originally developed from compression moulding, to allow production of more complex parts incorporating holes, recesses or inserts [2]. The result was a process whereby the mould was closed first and the moulding material then transferred by a compressive action into the cavity. A number of variations exist as this method is used for the production of thermoset parts as well as for mixed plastics. The process used for mixed plastic waste is now described.

Material is fed from a melt hopper into the heated barrel where it is homogenised and plasticated. It is then fed into a melt accumulator, which meters a fixed weight of material at low pressure into a partially open mould (as opposed to high pressure in the injection moulding process). This is illustrated in **Figure 6.20**. When filling is achieved, the press closes the mould and the material is compressed, as shown in **Figure 6.21**. When the moulding has cooled and has dimensional stability, it can be removed. The low clamping forces required by this process make equipment costs lower than conventional injection moulding. However, it does not lend itself to



**Figure 6.20** Transfer moulding Stage 1: Material transferred to cavity, tool closed



**Figure 6.21** Transfer moulding Stage 2: Material compressed to form moulding

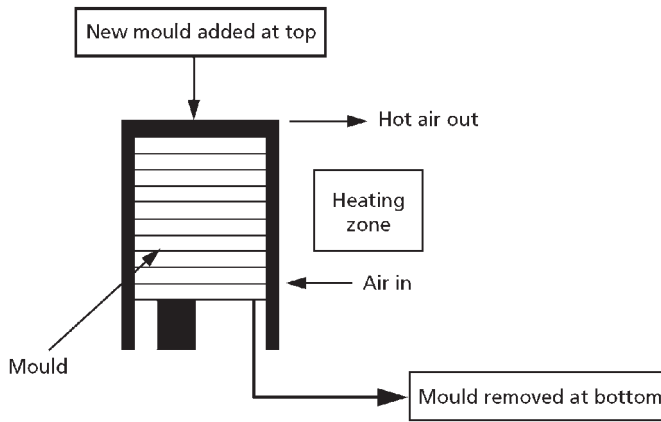
produce intricate parts and can best be applied to fairly simple parts similar to those produced in the compression moulding processes. One such application is pallets. This process is applicable to both mixed and unmixed plastics. The degree of other contamination that the process can tolerate, for example metal, depends on the design of the extruder and the extruder nozzle. Providing that contaminants are small enough and that sufficient plastic material is present to allow them to flow through the machine and out of the nozzle, no problems should be encountered.

### **6.9.3 Sinter Moulding**

The sinter moulding process can be used with a broad variety of mixed plastics. The process is tolerant to contamination from materials such as aluminium and paper, and panels made with waste wood chips have been manufactured [3]. The formulation can also be varied to produce mouldings with a range of properties for use as panels, sound proofing or packaging materials.

In this process plastic flake is plastified in a heated mould and subjected to pressure.

The material passes through a metal detector to remove large metal fragments and is shredded and dosed into moulds. These



**Figure 6.22** Sinter moulding process

then pass through a tower from top to bottom, where they are heated. The compressive pressure increases the further the mould travels down the tower. The lowermost moulds are cooled with ambient air, which then, after additional heating by means of a radiator, is conducted upwards in counter-flow to the moulds. This is shown in **Figure 6.22**. This process allows the production of large area panels of up to 60 mm thickness, with natural finish or lamination in the same operation. An advantage of this process is that the raw material can include the heavy fraction from the density separation of re-granulation plants and materials do not require cleaning prior to processing.

## **6.10 Conclusion**

An overview of the processes discussed in this chapter is given in **Table 6.1**. Whilst primary mechanical recycling will continue to be common practice amongst plastics processors, secondary recycling

Table 6.1 Comparison of processes					
Process	Complexity of parts	Forming action	Mould	Plastic types	Tolerance to contaminants
Extrusion	Fairly simple profiles	Extrusion	None	Single	Low
Injection moulding	Complex	Injection	Closed	Single	Low
Co-injection moulding	Complex	Injection	Closed	Single layers	Low
Compression moulding	Simple	Compression	Closed	Single	Medium
Extrusion blow moulding	Complex	Inflation	Closed	Single	Very low
Multi-layer extrusion blow moulding	Complex	Inflation	Closed	Single layers	Very low
Injection blow moulding	Simple	Inflation	Closed	Single	Very low
Film blowing	Simple	Inflation	None	Single	Very low
Intrusion moulding	Simple	Compression	Open	Mixed	High
Sinter moulding	Simple	Compression	Open	Mixed	Very high
Transfer moulding	Simple	Compression	Closed	Mixed	High

is subject to both practical and economic limits for use. Success depends primarily upon the economics of sorting to obtain single polymer materials, and knowledge of material provenance and degradation history. Processes adapted from conventional machinery to take more highly contaminated feedstock exist, however they are

limited in application to wood replacement type profiles and panels and cannot overcome the inherent limitations in the make-up of their feedstock. Even these processes also generally require feedstock to have undergone some preliminary sorting. The next chapter will look at ways to upgrade recycle materials in order to improve upon their properties for mechanical recycling applications.

## **6.11 Case Study: Plastic Lumber**

Recycled plastic is finding use as a wood replacement product. It does not splinter, rot or warp like conventional wood. It does not require preservation treatments and its lifetime can exceed over 50 years. There are now a number of plastic lumber type products available ranging from those made of entirely of one material, generally HDPE, to mixtures of plastic, wood, rubber and other materials. A number of factors are pushing the use of plastic lumber, especially in the USA where alternatives to hardwood lumber have appeal on environmental grounds. The market in the USA is estimated to amount to \$10 billion [3] and the industry is expanding rapidly.

Although plastic lumber has not yet been approved for load bearing applications, the American Society for Testing and Materials (ASTM) are in the process of setting up standards to differentiate between plastic lumber suitable for decks and those with the strength to act as railroad ties and bear locomotive weights. A number of standards already exist for plastic lumber, for testing flexural or compressive strength for example. Generally plastic lumber can be used in applications where hardwood is used. This includes construction, marine applications (where it is especially useful as it will not rot and does not need to be treated with preservatives), docks, all-weather furniture and fencing.

High profile projects include a pedestrian bridge made of recycled plastic in Greene County, New York, USA and plastic lumber

bobsled runs at Lake Placid, New York, USA. The bridge was made from one million milk jugs and detergent bottles reinforced with fibreglass. Its expected lifetime is 20-30 years. High profile projects like these should ensure that the market for recycled lumber continues to expand.

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# 7 Additives for Recyclates

## 7.1 Introduction

The two biggest problems associated with plastics recycling of post consumer products are:

1. The degradation of the plastics as a result of both processing and service life, and
2. The difficulties associated with getting acceptable material properties when processing mixed plastics [1].

To slow down the degradation of plastics, stabilisation additives are employed. Other additives such as fillers or modifiers can be incorporated to improve the properties of the recyclates. These modifiers can also be of benefit in mixed plastic fractions. First the issues associated with the degradation of materials will be discussed.

## 7.2 The Degradation of Plastics

Due to their chemical make-up, most plastics are susceptible to damage from the influence of the environment due to the action of light, heat and weathering. This ageing process is accompanied by a drop in both the visual (commonly seen in a yellowing of white carrier bags) and mechanical properties of the plastic, and it affects both virgin and recyclate materials alike. Plastics are also

susceptible to damage from the shear force that can arise during standard manufacturing processes and granulation. This action is accelerated by the high temperatures involved. The result is chemical degradation due to molecular damage in the form of chain cleavage, crosslinking or the formation of a series of double bonds.

Waste plastics, therefore, will have degraded to some degree following their original usage. The level of this degradation depends on the polymer type, on thermal and shear stress history and on the initial stabilisation. Additives are commonly added to plastics to inhibit or slow down these reactions.

### **7.3 Restabilisation of Recyclates**

Most plastics processors will reprocess their waste as a matter of course. It reduces their raw material costs as well as the cost of waste disposal. Often this material is simply fed back into the system along with virgin material. This presents few problems providing attention is paid to cleanliness and the reprocessed material has not been contaminated with dirt, oil or other types of material. The amount of degradation undergone by these materials will be dependent on the processing conditions that they were subjected to and the levels of stabilisers present. If these materials are to be used for a second application, it is possible to restabilise them. For this, knowledge of the type and amount of stabiliser originally used is required. Some stabilisers are consumed in the process of protecting the plastic and these materials need to be kept at optimum levels to ensure continued protection. Further testing may be required to assess the stability (both processing and long-term).

### **7.4 Testing the Effects of Stabilisers**

In order to measure the stabilisation of a plastic, be it virgin or recyclate, information is required on the effects of processing, heat and light.

### **7.4.1 Processing Stability**

A common method to investigate processing stability is through the repeated cycling of a sample, such as by extrusion or injection moulding. Mechanical tests such as tensile and impact and rheological tests such as MFI (melt flow index) can then be used to see if changes in the properties of the plastic are occurring. Methods of this type were introduced in Chapter 2.

### **7.4.2 Heat Stability**

When discussing heat stability, there are a number of different measurements that come under this term:

- (1) The temperature at which the plastic decomposes, which can be measured by techniques such as differential scanning calorimetry (DSC). DSC measures the heat output from the polymer as it is heated up or cooled down. It can be used across a wide range of temperatures from -180 °C to above 600 °C. This technique also permits the measurement of changes occurring in the plastic, which gives information on polymer properties, such as the melting point and the temperature at which thermal degradation occurs.
- (2) The maximum temperature at which the plastic can be satisfactorily processed without changes in colour or other problems. These problems would include decomposition of the polymer or other additives employed, for example colourants.
- (3) Often plastics are employed for applications where they may be subjected to prolonged use at elevated temperatures, for example, as the body of a kettle. For this type of application, data is needed as to how the material will react in service. This is usually tested by oven ageing a sample for a suitable number of hours to reflect those that are to be expected when the plastic is being used in a component.

### **7.4.3 Light Stability**

There are two ways commonly employed to assess light stability. One is to utilise artificial weathering equipment as described in ISO 4892 [2-4]. These machines can simulate weathering cycles by control of light (including ultraviolet (UV)) intensity, heat and humidity. Samples can be exposed to detailed, programmed cycles similar to those that components would be exposed to in service. The second method is simply to leave samples outside exposed to the natural environment. Different parts of the world have quite different climates: the established international standard, ISO 877 [5], requires outdoor weathering in Florida, Phoenix (Arizona) and Southern France. The effects can be measured in a number of ways. For example, the surface of the sample can be evaluated in terms of chalking, gloss and surface texture as a function of weathering time.

## **7.5 Stabilisers**

### **7.5.1 Thermal Stabilisation**

A combination of heat and oxygen will cause oxidation in the polymer, resulting in degradation. The mechanism is the formation of free radicals, which are highly reactive chemical species. This reaction can be observed, as the products will tend to show a discoloration to yellow or brown. Additives called antioxidants can be used to interrupt this mechanism. The chemicals most commonly employed are hindered phenols, which act as peroxide radical decomposers.

Other additives can also be employed in addition to hindered phenols. Additives called phosphites combined with hindered phenols, have a synergetic effect. This combination is especially effective for polyolefins.

Perhaps the most well known example of the use of additives to prevent thermal degradation is in the thermal stabilisation of polyvinyl chloride. The free radicals produced in this case are chlorine, leading to the formation of hydrochloric acid. The stabilisers must stop these reactions which lead to acid corrosion of the processing equipment.

### ***7.5.2 Light Stabilisation***

Light, especially in the ultraviolet range can induce photooxidation causing degradation and cleavage of the polymer chains. To deter this effect, three classes of additives can be employed. These additives are usually termed UV absorbers, quenchers (scavengers) and radical traps.

#### ***UV Absorbers***

These are among the oldest light stabilisers and work by absorbing the harmful UV radiation and converting it to heat energy. By absorbing these rays they protect the vulnerable polymer chains. Examples of additives of this type are benzophenones and benzotriazoles.

#### ***Quenchers***

Quenchers contain chromophores (light-absorbing species) which absorb energy and convert it into less harmful forms. Most commercially available quenchers are nickel compounds.

#### ***Radical Traps***

One of the effects of light on the plastic is the formation of radicals. Radicals are highly reactive species and can cause rapid

degradation. To prevent further damage to the plastic, these can be ‘mopped up’ using radical traps. The most important radical traps are known as *hindered amine light stabilisers* (HALS). It should be noted however, that once all the additive has been consumed the degradation process will commence. For this reason, it is important that the correct levels of additives are employed.

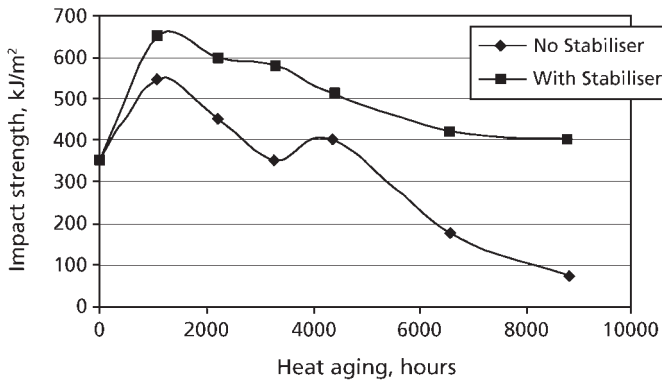
Interestingly, the mechanism of the radical trap can also be applied to flame retardant technology in plastics. Here however, instead of the chemicals trapping damaging UV rays, the additive helps to limit the combustion process. Different chemicals are employed for this purpose but the mechanisms of action are very similar.

### **7.5.3 Additive Combinations for Specific Purposes**

The additives used in a particular plastic will depend very much on the intended application. Outdoor applications for example, will require both light and heat stability.

Bottle crates, made from a single plastic, high-density polyethylene (HDPE), have been extensively studied. The use of 100% recyclate without further stabilisation resulted in a loss of mechanical properties, cracking and colour fading after six months. However, when HALS and UV absorbers were incorporated, the recyclates retained their properties for more than four years. **Figure 7.1** shows the effects of stabilisation on impact strength retention [6]. Further studies on heat ageing found that restabilisation using a combination of processing stabilisers, light stabilisers and HALS, effectively restabilised the recyclate for further reuse.

It is clear that for successful applications care must be taken to ensure that the recyclates are adequately protected with suitable additives, depending upon their future use.



**Figure 7.1** The effect of heat ageing on the impact strength of HDPE

## **7.6 Modifying the Properties of Plastics Through Incorporation of Miscellaneous Additives**

### **7.6.1 Degradable Plastics**

Since plastics can comprise up to 40% bulk of all the waste in landfill, another waste management strategy is to speed up their chemical breakdown once they enter the waste stream [5]. This is not recycling, simply an attempt to limit environmental damage. Plastic litter that is dropped will thereby harmlessly degrade in the natural environment. It makes good sense.

In this chapter it has been shown that stabilisers can protect plastics from environmental damage. However, one solution to the problem of plastic litter is to utilise this chemical breakdown and make plastics degradable. Additives can be used to speed up the process rather than delay it. There are two key mechanisms which can be usefully harnessed for plastics degradation: photodegradation and

biodegradation. Photodegradation involves the action of sunlight, specifically in the ultraviolet regions. A biodegradable compound is one that is consumed by microorganisms in the environment, similar to the process of composting natural organic matter.

One of the problems associated with degradable plastics is that if they contaminate normal recyclates they can cause degradation problems in future service. Another problem is that however well a material is designed to degrade in the environment, the process will be greatly affected by climatic conditions, particularly exposure to sunlight or extremes of temperature. These kind of climatic conditions cannot be accurately predicted and hence neither can the breakdown time of the plastic material. Premature failure in service may be the undesirable result.

Degradable plastics have found limited use in agricultural applications and food packaging. The balance between recycling plastics and incorporating degradation accelerating additives will depend very much on future legislation and technologies in waste management control. A further factor will be the growing influence of biopolymers. These will be dealt with in Chapter 11 and it is important to distinguish between plastics made from oil reserves that have been the focus of this book so far and plastics made from renewable resources such as crops that will be discussed later.

At the beginning of this chapter, two major problems with recyclates were identified. The first, degradation, has been dealt with in previous sections. The second, the problem of dealing with mixed plastic wastes will now be addressed.

### **7.6.2 Compatibilisers**

The major problem with mixing plastics is the fact that they are generally immiscible with each other. However useful combinations of immiscible materials are not uncommon. Blending of existing



polymers to create new ones is a cost effective method to create new materials, since synthesising new polymers is both expensive and difficult. Blends were first introduced in Chapter 3. A common commercial example of a blend is high impact polystyrene, which is a blend of polystyrene and polybutadiene particles. Polybutadiene is a type of rubber that gives the blend greater impact resistance than could be achieved with polystyrene alone. Polystyrene has a high modulus. The combined result is a material that is both reasonably strong and has good impact resistance.

For a material to be defined as a polymer blend it must consist of at least two species of polymers and the minor component must exceed 2% by weight. Blends can be either miscible or immiscible (These terms were introduced in Chapter 3.)

Terminology can be quite confusing on the subject of blends and the science behind miscibility is quite complex. Interested readers are referred to the book by Akovali and co workers [8].

The level of dispersion of one polymer component in another is very important to the properties of blends. Adding compatibilisers to immiscible blends provides a way to increase the dispersion of one component in another. The compatibiliser is tailored to bond with polymers that do not bond with each other, in effect creating a type of 'glue' to hold the polymers together. This acts to stabilise the system for the rigours of processing and enhance adhesion of the components with a resultant improvement in mechanical properties.

Compatibilisers are commercially available for combining a range of materials and this technology can also be applied to recycle blends. The advantages of this are: the removal of the requirement for costly and/or difficult separation processes, and the production of commercially valuable materials. The compatibilisers can be added during reprocessing usually at levels of around 2-5%. The cost of the compatibiliser must be taken into account, but this can

be offset against the elimination of the cost of separation and the gain in properties and commercial value.

A number of companies market compatibilisers, for example DuPont market a range called Fusabond [9]. Generally each grade will offer a specific polymer interaction, for example DuPont MZ-203D acts as a compatibiliser between polypropylene and polyamide. Some companies market universal compatibilisers for use with mixed plastic wastes, these tend to be expensive and less effective, since generally a compatibiliser needs to be optimised for specific blends. This, of course, presents a problem with mixed plastics waste, where a constant ratio of one material to another is unlikely to be achieved as the nature of the components is likely to fluctuate. However, where contamination of one material with another is likely, compatibilisation is an effective method to eliminate the need for sorting and improve the resultant mechanical performance of the contaminated material.

### ***Conclusion on Blends***

In general, polymers cannot be homogeneously mixed with one another. However, mixtures of polymer may enable many of the characteristics of the blend components to be retained and blends have great commercial importance. Adhesion and dispersion between the polymers can be enhanced by commercially available compatibilisers. These work best when tailored to specific combinations of materials.

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# 8

## Other Methods of Recycling and Waste Disposal Options

In Chapter 1, chemical recycling and energy recovery were introduced as alternatives to mechanical recycling. We have seen how plastics can be reprocessed if they are pure streams, if they can be sorted, or if suitable blends can be obtained. We have also seen potential applications for mixed plastics where the quality of the final product is reduced, but the inherent properties of all plastics such as rot-resistance can be utilised. An example of this is in wood replacement applications. However, material that is highly contaminated and mixed may be difficult or perhaps even impossible to recycle mechanically. Remember that cleaning and sorting can be difficult, costly and laborious.

Examples of highly mixed and technically challenging wastes can be found in domestic household waste, electrical and electronic waste and end-of-life vehicles when they have been shredded. If it is not practical to sort and mechanically recycle these wastes, what are the alternatives?

Other technologies for the recovery of materials will now be considered, these are listed in **Table 8.1** along with the definitions already introduced in Chapter 5 [1]. Chemical recycling technologies, like mechanical recycling, place restrictions on the quality of feedstock that they can handle. Energy recovery is less demanding on the requirements for sorting of individual plastics. These disposal methods offer an alternative to the use of landfill. First, however, we will revisit Chapter 2 and see what methods are available to dispose of thermoset waste.

Table 8.1 Standard names of processes for plastics recycling	
Term	Type of Recycling
Primary recycling	Mechanical recycling
Secondary recycling	Mechanical recycling
Tertiary recycling	Chemical recycling (Feedstock recycling)
Quarternary recycling	Incineration (Energy recovery)

## 8.1 The Case of Thermosets

In Chapter 2 the reasons that thermosets could not be reprocessed in the same way as thermoplastics were introduced. Thermosets are crosslinked, meaning they cannot be re-melted and reprocessed in the same way as thermoplastics. Until relatively recently thermosets were considered non-recyclable but with recyclability becoming an ever increasing criteria for material selection, the thermoset business faced a serious threat if ways could not be found to overcome this hindrance to market potential.

To tackle these technical challenges a series of companies and trade associations were set up across the globe to develop recycling methods for these materials. These groups are ERCOM Composite Recycling GmbH (Germany), VALOR (France), SMC Alliance (USA) and the FRP Forum (Japan).

A German company, BASF, patented one such process. It is known as particle recycling and involves recycling a common thermoset material called sheet moulding compound (SMC). This is a thermoset material mainly used for structural purposes and has a high level of fibre reinforcement in it. A closed loop system was proposed and set up, with the first recycled parts being used in 1992. The process involves several stages. The

waste SMC material is hammer milled to reduce its size and then separated by size. The coarse material is returned to the process and the finer material is sieved to give several grades of a fibrous reinforcement. The graded fibres are then supplied to the manufacturers of virgin reinforced plastics. They are able to replace traditional fibres using between 10% and 30% of the recycle fibre without any adverse effect on quality. In fact, they claim a 10% weight saving [2]. This system can also be applied to thermoplastics reinforced with glass fibre. Currently the best approach to recycling SMC is to grind it up into filler and fibre fractions for use in new markets.

Thermosets have been used successfully as functional fillers for thermoplastic materials [3]. Fillers are cheaper than polymer and can help reduce the cost of the final compound. In this particular process, the thermoset is physically and chemically modified. When it is combined with polymer it produces enhanced material properties. The modifications are necessary to optimise the bond between the recycle and the virgin polymer. This work was carried out as part of the Recycling and Recovery from Composite Materials (RRECOM), a UK based alliance of 16 companies and two universities, Brunel and Nottingham.

We have seen previously that if materials are finely dispersed in another polymer matrix, they do not cause great mechanical weakening. Powdered thermoset scrap can find use as a material held by adhesive resins, as filler in thermoplastics or as part of a new uncured thermoset matrix. The glass reinforcement can generally be recovered for re-use.

Using recovered thermosets as raw materials in these ways, involves further examples of mechanical recycling. The economics for the success of mechanical recycling usually depend on the cost of the washing and sorting stages. In using recycled thermoset merely as a cheap filler rather than in 'added value' applications, it is unlikely

that the costs of recovering and grinding can be met. However, there are other methods available for recycling and recovery using chemical means.

## **8.2 Chemical Recycling**

One other method is chemical recycling, where the polymer is broken down into smaller molecules that can be easily separated from impurities.

In chemical recycling, also known as feedstock recycling, plastics are used to make raw materials for petrochemical processes. Common examples of such processes are cracking and hydrogenation.

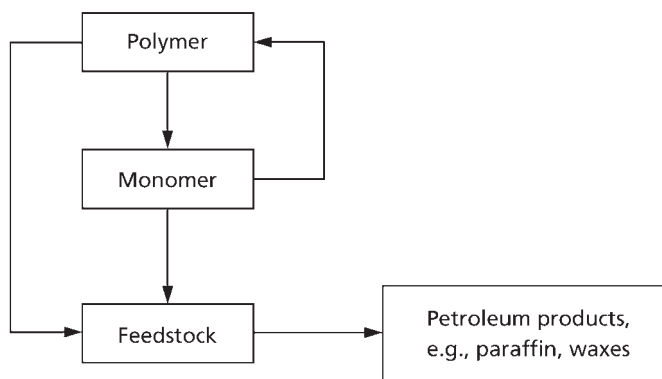
Processes like these place restrictions on the types of materials they can handle and each method has slightly different restrictions and tolerances. Generally, however, these processes cannot handle untreated waste and sorting is necessary to remove fractions containing heavy metals, fillers and halogen compounds.

A simple way to imagine chemical recycling is that it is the reverse of the process used to create the polymer chains. Going back to the basics of Chapter 2, polymers are made up of a series of monomers joined together in a polymerisation process. Chemical recycling is often a depolymerisation or degradation process. Here, the macromolecules are broken back into smaller chemical units. Once the monomer is recovered, it can be used to make new polymers.

A second type of reaction takes the polymer back one stage further to produce feedstock that can be used to produce the monomer or other petroleum products such as waxes and paraffin. The relationship between these two routes is shown in **Figure 8.1**.

Chemical recycling is especially suited to polymers formed by condensation reactions such as polyethylene terephthalate (PET),





**Figure 8.1** Chemical recycling of polymers

Nylon and PU as the process is the reverse of the one used to create them. However, the waste must be reasonably free from other polymers or impurities.

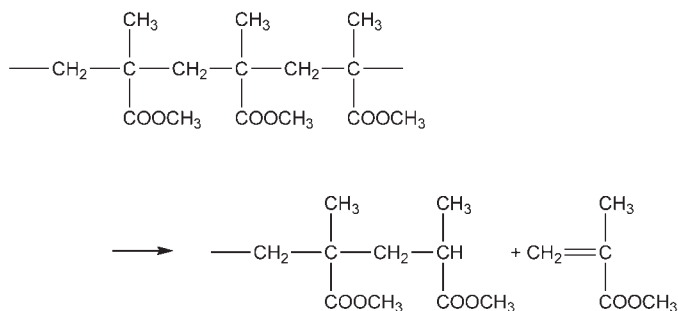
These technologies are exploited in industry. For example, the depolymerisation of Nylon 6 has been particularly well researched and has been practised since the 1960s [4]. In 1997, DSM Chemicals North America and Allied Signal commissioned a worldwide facility to depolymerise Nylon 6 from carpet waste [5]. It opened in 1999 and 25% of these depolymerised monomer building blocks are used to make new nylon 6 compounds, marketed under the tradename AKULON ReCap with a particular focus towards their use in automotive applications [6].

The recovery of polyester materials such as PET can be achieved using a process called hydrolysis. It is the reverse of the reaction (polycondensation) used to make the polymer in the first place, in that the addition of water or water vapour to the process causes decomposition. DuPont hold a patent on one such process that converts the polyester back to carboxylic acid [7]. Hydrolysis is

also used for the breakdown of polyurethane (PU) foams. However, the PU reaction is slightly more complicated than the one for PET, as there may be other by-products. This can produce mixtures of substances that may require further separation.

A pilot plant was opened in the UK by ICI in 1998 to look at the feasibility of chemically recycling polyurethane, their method being a process called split-phase glycolysis [8]. Like hydrolysis, the method is complicated by the presence of by-products. Commercial depolymerisation units using the glycolysis of polyurethanes operate in Germany, Austria and Denmark [4]. The requirement for separation can be avoided in this case by further chemical reactions. The basic chemistry involved in these reactions is presented by Ehrig [9] for those who require further details.

One material particularly suited to depolymerisation is polymethyl methacrylate (PMMA), more commonly known as acrylic. The route for depolymerisation is shown in **Figure 8.2**. To show the long history of depolymerisation technology, a process to depolymerise PMMA was developed and patented in Germany as far back as 1949 [10]. However, this method lead to the recovered material being contaminated with lead, which obviously limits application for this particular process. An alternative and more



**Figure 8.2** Depolymerisation of PMMA

environmentally friendly method has been developed using a twin-screw extruder, which heats material beyond its depolymerising temperature. The monomer is recovered as a gas and condensed into a barrel [11]. This process is still at the laboratory stage. In 1997, ICI Acrylics and Mitsubishi Rayon announced a joint venture to develop more efficient depolymerisation technologies for PMMA [12]. The PMMA is crushed and thermally treated at 500 °C to produce methyl methacrylate monomer, which can be used to produce new PMMA materials.

### **8.3 Thermal Conversion Technologies**

Thermal processing can be defined as the conversion of solid wastes into conversion products with a release of heat energy. It can serve two purposes: volume reduction and energy recovery.

There are a number of different categories usually distinguished by their air requirements.

1. Pyrolysis: thermal processing in the absence of oxygen,
2. Hydrogenation: pyrolysis but in a high hydrogen or carbon monoxide environment, and
3. Gasification: partial combustion in which a fuel is deliberately combusted with limited air.

These methods can offer significant benefits compared to simply incinerating polymeric materials.

- Environmentally cleaner process routes producing significantly lower emissions.
- The reduction in the amount of waste residue and its bulk density enables cost reduction for subsequent transport and handling as landfill.

- Increased energy density - more energy is recovered from the plastic by these methods than by simple combustion.
- Conversion to fuel results in higher overall efficiencies than standard combustion.

### **8.3.1 Pyrolysis**

Pyrolysis can be split into two types, both carried out in an oxygen depleted environment. Low temperature pyrolysis is a depolymerisation technique, whilst high temperature pyrolysis is a thermal degradation technique.

Low temperature pyrolysis (450-600 °C), also known as cracking, is a depolymerisation technique. The main products include potential feedstocks for polyolefin production as well as higher boiling liquids and waxes. Whilst laboratory cracking of simple polymers is widely understood, mixtures of polymers including associated fillers, additives and other impurities make commercial scale-up more difficult. BP Chemicals have been developing this technology, starting on a pilot plant scale in Grangemouth, UK [13]. Industrial scale up trials have been completed successfully. Wide scale implementation is now being considered.

High temperature pyrolysis (750-950 °C) is a thermal degradation technique and can be used for co-mingled wastes. It is mainly used for waste that is so highly mixed or contaminated that standard combustion would give rise to pollution hazards from combustion products. The costs of scrubbing (cleaning effluent gas streams) are favourable when compared with standard combustion: pyrolysis produces 5-20 times less gas, which means that there is an increased concentration and binding of pollutants in the coke residue for easier disposal.

In a German study published in 1999 [14] it was found that problematic electrical and electronic waste could be successfully

recovered by pyrolysis at temperatures of 700-900 °C in the absence of air. Halogenated hydrocarbons in the waste were destroyed. The resulting oil and gas products were found to have high calorific values, which, although found to be unsuitable for use as feedstocks, could replace the fossil fuels used to heat the kiln. The metal containing pyrolysis coke could be treated in a copper smelter without further processing. The same study also compared the cost of mechanically treating this waste to recover the metal with the pyrolysis technique. The treatment costs for both processes were found to be similar.

### **8.3.2 Hydrogenation**

This is very similar to pyrolysis, but in this process the mixed plastic waste (MPW) is heated with hydrogen. As the molecules are cracked (the process is often termed hydrocracking), they are saturated with the hydrogen molecules to produce a saturated liquid and gaseous hydrocarbons. The synthetic crude oil produced is of a very high quality. It is necessary to keep the pressure of the hydrogen sufficient to suppress repolymerisation or the generation of undesirable by-products.

In 1992, a coal-oil plant in Bottrop, Germany, successfully trialed hydrogenation technologies with plastic waste. Some restrictions on feedstocks were necessary to optimise the efficiency of the plant. Its success requires close collaboration with suppliers to ensure suitable feedstocks.

### **8.3.3 Gasification**

Gasification technology is based on the use of partial combustion. It was originally developed for use with coal and oil. There are a number of variations, depending upon the type of gases used.

These include oxygen in the form of air, steam, pure oxygen, oxygen enriched air or carbon dioxide. The temperature required also depends on the type of fuel. It generally falls in the range 800-1600 °C. Gasification is favoured for fuel gas production since a single gaseous product is formed at high efficiency without requiring expensive and potentially dangerous separation plants. The synthetic gas produced can be classified according to its composition, heat value and application. The bulk of the carbon present in the waste feedstock is converted to gas leaving a virtually inert ash residue for disposal.

## **8.4 Energy Recovery**

Energy recovery can be defined as incineration to recover inherent energy.

Given that polymers are made from oil, it is not surprising that they are quite good fuel sources when they are burnt. The amount of energy that can be recovered depends on the calorific value of the material. Literature values tend to give an average calorific value of mixed plastic waste as 35 MJ/kg. When compared to paper (16 MJ/kg) and organic waste (3 MJ/kg), it can be seen that plastics give a relatively high energy return when incinerated.

There are a variety of methods used for energy recovery. One, pyrolysis, has already been discussed. Incineration, production of waste-derived fuel and gas recovery from landfill site emissions are three examples of energy recovery in action.

The UK tends to lag behind mainland Europe, Japan and the USA when it comes to using energy recovery technologies. For example, Japan uses 78%, Denmark 58%, and Luxembourg uses around 75% of its municipal waste for energy generation whilst the UK uses only 9%. This difference is mainly due to the acceptance of

### *Other Methods of Recycling and Waste Disposal Options*

landfilling as a waste disposal option in the UK. However, with the cost and restrictions imposed on such disposal expected to increase, alternative methods will come to the fore.

Many countries throughout Europe already use municipal solid waste combustors with state-of-the-art energy recovery and flue gas cleaning technology to produce high percentages of the domestic electricity requirements. Energy recovery is even more efficient if the combustor is linked to a municipal localised heating system for the supply of hot water and process steam. In Paris, France, residential buildings in some areas are equipped with combustors. Thereby domestic waste is incinerated locally and used to provide low cost heating for the residents.

The world's first electricity generating plant to run on nothing but waste plastic fuel is in Japan. The plant consumes 700 tonnes of waste plastic a day and provides power for 30,000 Japanese homes.

MPW can also be used as a secondary fuel source in cement kilns [15] and steel foundries. Ground plastic waste is added to the main fuel source and can replace up to 16% by weight of the primary fuel. This secondary fuel source has been found to reduce the emissions of nitrogen oxides and sulfur oxides and it is estimated that up to 40% of the primary fuel can be replaced by MPW in the future.

The main methods of plastics recycling have now been introduced, the next chapter will deal with how all those involved in the supply chain can aid in improving recycling potential. This involves considering recycling at all stages of product development from the concept and design stage right through to recovery.

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# 9

## Creation of a Recycling and Recovery Infrastructure for Plastics

This chapter steps away from the technology of plastics recycling to look at the bigger issues facing the plastic recycling industry. Chapter 1 highlighted the issue that for plastics recycling to be sustainable long term, a balance must be reached between the technology, economics and the environmental issues. The plastics recycling industry must be self-supporting. In order for this situation to be reached a number of criteria must be met:

1. The development of cost effective sorting and recycling technologies capable of creating quality materials from waste materials.
2. The design of parts that can be recycled easily (design for recycling, DFR).
3. The design of parts that can be disassembled easily (design for disassembly, DFD).
4. The creation of markets for recycle.
5. The creation of a recycling infrastructure, allowing post consumer waste to move through the reprocessing chain in a timely and effective manner.
6. Quality must be assured.
7. The 'inferior goods' tag attached to recyclates must be removed.

## **9.1 Development**

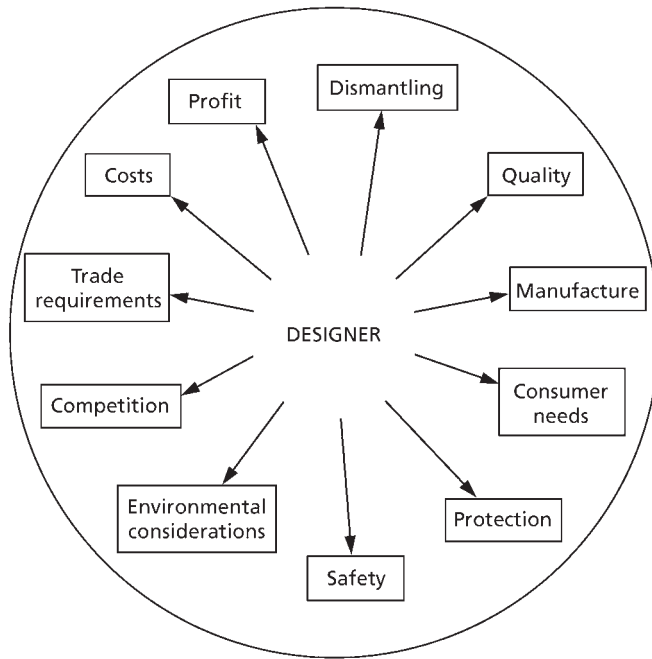
For the development of new recycling technologies sufficient investment is required in both research and development (R&D) and new machinery and technology. Research needs to be targeted at the areas of greatest industrial need and, once developed, technologies need to be successfully transferred to industry. Best practice guidelines need to be available to highlight and disseminate the most up-to-date and effective treatment methods.

Recycling interests do not start at the end of a product life. They begin with the conception of a new product. By introducing the need for recyclability in the design stage, the problems of waste disposal can be reduced. If a product is part of a bigger component, disassembly needs to be considered too.

For components that require disassembly such as white goods, automobiles and electrical waste, any successful recycling strategy must ensure the easy and cost-effective removal of parts. If disassembly is difficult and time intensive, the cost effectiveness of recycling falls. Therefore, parts should be designed with disassembly in mind.

**Figure 9.1** shows some of the possible considerations a designer may be faced with. Areas highlighted in **Figure 9.1** may also conflict with each other. For example, increased recyclability may incur a much higher cost.

A consideration of the lifetime of the product is also needed. For example, packaging products may have only two years before entering the waste stream, whereas a plastic part on a car could have a seven or eight year lifespan. Other components such as underground pipes may have lifetimes of twenty years, or perhaps longer. What recycling technologies will exist in twenty years time



**Figure 9.1** Design considerations for recycling

and what legislation will be attached to their use? A designer has no way of knowing, but can design for recycling based on current technologies. It may be only in twenty years time that the success of that design can be judged.

Design for recycling has particular significance in the automotive arena where recycling is becoming an increasingly important issue.

Design for recycling guidelines have been produced by the automotive company, Ford, and include the following [1]:

- Quick and easy removal of parts and fluids for cost effectiveness.
- Parts marking: the benefits of easy identification of generic material types were discussed earlier, it is a practise with proven success in the packaging industry.
- Material selection: this includes usage of materials that can be recycled, avoiding mixtures of incompatible materials and reducing unique material types, all of which make the recycling process easier. By reducing the number of different plastics used, segregation becomes easier and more efficient. Two examples where specifying only one material could improve recyclability are the car bumper (acrylonitrile-butadiene-styrene and polypropylene (PP)) and in yoghurt pots (polystyrene and PP). If all parties agreed to standardise the use of just one type of plastic for these products, recycling of both becomes easier.
- Materials of risk to health and the environment: how to eliminate them or best deal with associated hazards.

Ford's programme of Total Waste Management has meant not only an increase in recycling, but also a reduction in waste production in the first place.

As an aside here, in manufacturing much emphasis has been placed on design for manufacture. This can both aid and hinder design for disassembly (DFD) and the recycling process. What is good for one is not necessarily good for the other. For example, a part that is easy to fit, may not necessarily be easy to dismantle. It may be necessary to compromise so that both can be satisfied.

### **9.3 Developing Recyclate Markets**

Once the materials enter the recycling stream, both applications and consumers must be found for recyclate materials. This creates demand and allows recycled material to have economic value in the marketplace. If the associated value of the material is sufficient, then recycling of the material will be both cost effective and sustainable. These materials must compete against virgin materials in terms of both cost and quality. One important trend in this area is that plastic manufacturers themselves are marketing grades containing recycled materials, which takes away much of the onus from designers in terms of finding ways of incorporating recycled materials. It also increases confidence in the quality of recyclate materials. The lack of knowledge on consistency of quality and properties, often a cause for resistance to switch to recyclates, is removed.

Aided with standards for these materials, new potential uses for recyclates can be more easily identified. Designing components for disassembly and recycling, and setting up an infrastructure capable of handling the post consumer materials are issues that must be addressed.

With the exception of food contact and medical applications, there appears to be a very healthy market for recyclates to compete in, that being the virgin market. The problem appears to be more issues of price, price fluctuations and consistency of supply. When specifying a product a designer needs to ensure that the supply of that material is adequate for the lifetime of their product.<sup>9.4</sup>

Logistics

The success of the entire procedure relies on the infrastructure being in place for the collection of the materials for recycling. Logistically, for a reprocessing plant to be viable, it needs to be close to a constant source of supply. This problem occurs mainly

because of the inherent low density of plastics. They need to be baled in order to get a good weight and hence a reasonable value of plastics to cover the costs of transporting loads. Reliable and sustainable sources of waste need to be identified, to enable both sufficient quantities and constant supply to have confidence in specifying recyclate materials. 9.5 Quality

Standardisation programmes such as those championed in the UK by groups such as WRAP and CARE will ensure that the same kind of quality control is attached to recyclate as has become the norm with virgin materials. 9.6 Education

It is also necessary to educate and inform all those involved in plastic waste management as to how they can aid in reaching recycling targets. This would include the general public, who may in a limited manner assist, for example in returning plastic bottles and other recyclable goods to recycling centres, or by sorting their rubbish into kerbside boxes. They can also exert commercial pressure by choosing to buy products made with recycled materials.

When these points have been addressed, the ability to cope with the ever changing demands of the plastic recycling marketplace should be assured.

One final note, it should be remembered that many of the issues addressed here do not apply only to plastics. In the UK, 65 million tonnes of waste go to landfill every year.

‘This means that every hour we throw away enough rubbish to fill the Albert Hall’

(Vic Cocker, Chairman, The Wrap Business Plan: Creating markets for Recycled Resources, 2001).



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## Suggested Further Reading

2. G. Tchobanoglous, *Integrated Solid Waste Management: Engineering Principles and Management Issues*, McGraw-Hill Inc., New York, NY, USA, 1993.
3. *Plastics Waste Management: Disposal, Recycling and Reuse*, Eds., N. Mustafa, Marcel Dekker, New York, NY, USA, 1993.
4. R. Waite, *Household Waste Recycling*, Earthscan Publications, London, UK, 1995.

## Useful Web Sites

The following sites also provide links to a number of other internet resources:

- British Plastics Federation (BPF)  
[www.bpf.co.uk](http://www.bpf.co.uk)  
Accessed September 2007.
- American Plastics Council (APC)  
[www.plasticsresource.com](http://www.plasticsresource.com)  
Accessed September 2007.
- RECOUP  
[www.recoup.org](http://www.recoup.org)  
Accessed September 2007.

*Introduction to Plastics Recycling – Second Edition*

- Waste and Resources Action Programme (WRAP)  
[www.wrap.org.uk](http://www.wrap.org.uk)  
Accessed September 2007.

# 10

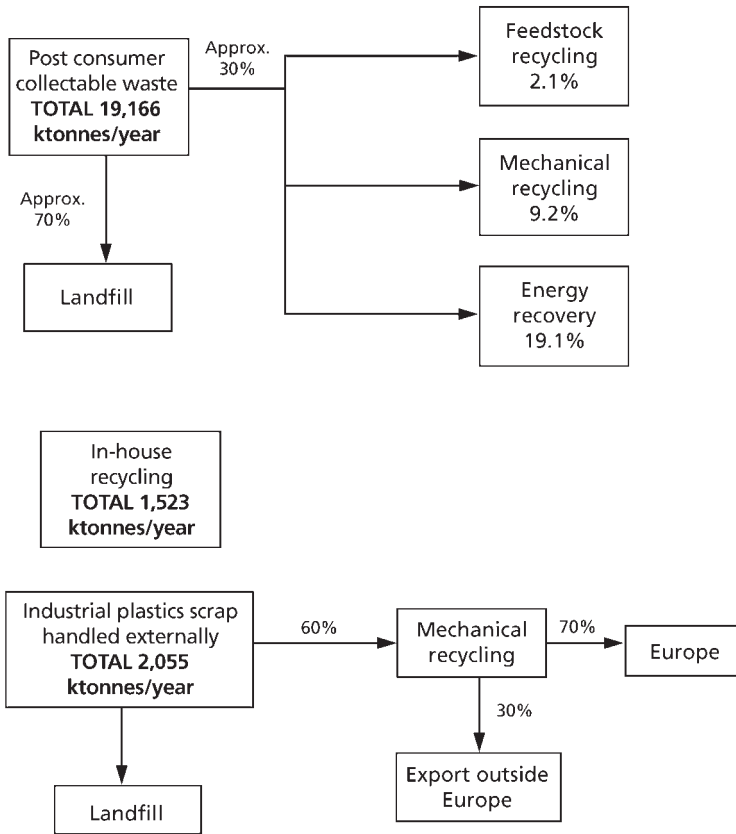
## The Problem in Perspective: Europe

Plastic production accounts for about 4% of total oil consumption. Whilst this is not a vast percentage, it still represents a significant potential energy resource saving if plastics can be recovered. However, the main driver for plastics recycling is not energy recovery but landfill avoidance.

The majority of plastics waste is produced by the packaging sector as shown in **Table 10.1**. It is therefore not surprising that packaging has been targeted as the prime area for material recovery.

Table 10.1 Breakdown of plastic consumption by sector	
Sector	Plastic consumption (%)
Packaging	41
Building/construction	19
Household	18
Electrical/electronics	8
Automotive	7
Other	7

Currently, in Western Europe, only about 30% of post consumer plastic waste is recovered in the form of materials or energy. The remaining 70% is disposed of as landfill. A breakdown of



**Figure 10.1** Plastic waste recovery routes in Europe in 1999.  
(Source: APME, 2001)

recovery routes is shown in **Figure 10.1**. Statistics on the volumes of material being recycled are often difficult to obtain, however, reliable information must be available if recycling targets are to be monitored. As recycling systems and infrastructures develop, the reporting systems and quantitative data required should be easier to obtain in future. From the data that is available, inhouse recycling

accounts for some 1.5 ktonnes, traded industrial scrap recycle at 1.1 ktonnes and post consumer waste mechanical recycling at 1.8 ktonnes. Therefore total mechanical plastic recycling in Europe is estimated as being in excess of 4 ktonnes/year [1].

The most effective treatment of recyclates is also a matter for consideration. A study was undertaken in 1999 to provide an evaluation of waste management scenarios [2]. It is likely that this and similar studies of its kind will form the rationale of future European Union (EU) recommendations and legislation. It was found that if too much emphasis was placed on mechanical recycling, costs became prohibitive. Increasing mechanical recycling rates beyond 15% has no effect on efficiency and becomes very costly. Therefore diversion from landfill should utilise the full spectrum of recovery options.

## **10.1 Case Study: Packaging**

Recycling rates vary greatly across Europe, due to different legislative and environmental measures adopted by member states. The country at the forefront of implementing plastics recycling schemes is Germany. Packaging waste concepts introduced in Germany in June 1991 have provided much valuable data for the rest of the EU. The target set was 64% to be recycled by July 1995, based on a system of collection, sorting and recycling technology. The high environmental awareness present in the German population enabled high collection rates to be achieved. However, problems with mechanical recycling were soon exposed in trying to separate mixed plastic fractions. A less ambitious 15% recycling target was set across the rest of the EU. The Germans, however, pushed towards the higher targets resulting in breakthroughs in feedstock recycling technologies. Whilst high targets like these place considerable pressure on industry, they also initiate technological development. As recycling targets are increased, research and development becomes increasingly important.

<b>Table 10.2 Difference in EU legislation/instruments for plastic packaging recycling in 1996 [3]</b>			
<b>Country</b>	<b>Materials</b>	<b>Objectives</b>	<b>Instruments</b>
Belgium	Packaging waste	50% of packaging waste by 2001	‘Cost-plus’ system: collection of household waste financed by a fee.
Finland	All packaging waste	70%-85% of packaging waste recovered by 2001	Charges on non-refillable containers. Voluntary deposit-refund on plastic bottles. Shared producer responsibility.
Germany	Packaging	64% plastic recycling	Mandatory deposit/refund system. ‘DSD’ system responsible for collection and recovery of packaging.
Italy	Beverage containers, packaging waste	Recycling rate of 40% plastic, 15% plastic packaging waste recovery	Mandatory consortium. Raw material charge of 10% on virgin PE sold for film production. Waste disposal charges.
Spain	Recycling decree in preparation		
Sweden	All packaging waste	30% plastic recycled by 1997	Product charge on plastic packaging fillers and importers.
United Kingdom	All packaging waste	58% of packaging waste recovered by 2000 (plastic 16%)	Shared responsibility landfill tax.
<i>PE = Polyethylene</i>			

One problem facing Europe is the lack of synergy between the regulations of individual countries as regards plastic waste. This can create barriers to trade, cause logistical problems and inhibit the commissioning of large scale recycling facilities. Examples of legislative measures applied to packaging waste in 1996, in selected EU member states are given in **Table 10.2**. This table highlights the differences in implementing recycling strategies in the EU. Whilst Germany has the most advanced recycling systems, in 1996 Spain had yet to have any legislation in place on packaging.

More integrated policies such as the European Packaging Directive appear to be the way ahead. The problems of differences in the cost of the various recycling options, taking particular local (country) conditions into account should, however, not be overlooked.

**Table 10.2** illustrates the five different strategies adopted to stimulate recycling activity:

- Raw material charges (Italy)  
Objective: To increase the use of recyclates rather than virgin material
- Waste disposal charges (Italy/UK)  
Objective: Cover costs of waste disposal, reduce disposal and encourage recycling, also revenue source
- Waste product charges (Sweden/Finland)  
Objective: Encourage use of reusable materials, reduce waste, source of revenue
- Waste collection charges (Belgium)  
Objective: Encourage recycling and waste reduction
- Deposit-refund systems (Germany)  
Objective: Encourage the return of waste products for recycling or re-use.

Whilst all these systems have advantages/disadvantages, the use of different strategies again causes problems in setting up Europe-wide recycling systems.

A further issue worth mentioning is the concept of responsibility towards waste.

In **Table 10.2** both the UK and Finland have instruments of ‘Shared Responsibility’.

Extended Producer Responsibility is a concept that takes in the lifetime of a product beyond its initial manufacture. It encourages producers to consider the potential environmental impact caused by their products and promotes ‘Design for Recycling’ (as introduced in Chapter 9) at the earliest stage of component design. This is a very important and essential concept in dealing with the problems of plastic waste. It provides a very powerful incentive for manufacturing to become environmentally responsible in the future.

## **10.2 Integrated Product Policy**

Given the concerns raised by Extended Producer Responsibility, a public policy initiative was set up which encompassed the entire supply chain (including the consumer and supported at government level) to promote good environmental practice throughout the life cycle of the goods or service. This policy was termed an Integrated Product Policy (IPP).

In order to promote IPP, it is necessary for Governments to provide and enforce the necessary legislative framework, otherwise the economic interests of the individual parties often promotes an individual short term viewpoint rather than a shared long term interest in the wellbeing of the environment.



A key driver in IPP is to change perception and responsibility for products and their waste. Manufacturers are expected to consider an entire life cycle including design, production and disposal.

Once this is in place individual parties within any supply chain can initiate their own IPP. However it may be necessary to juggle a variety of factors such as regional legislation, international standardisation, any economic measures or incentives, perhaps some voluntary measures and, arguably most importantly for a commercially sustainable product, the expectations of the consumer to demand IPP sensitive products. IPP necessarily passes the cost for a more environmentally friendly product throughout the supply chain and for the consumer this means an increased product price. The consumer needs to buy into the idea as well, otherwise a product will fail once placed within the market place.

For the EU, the concept of IPP has been around since the 1990s, however progress has been very slow and timescales for a specific European IPP are not forthcoming. However key points were defined as being:

- Managing wastes
- Product innovation
- Market creation
- Transmission of information
- Allocation of responsibility

Defining a common understanding for what IPP was, disseminating best practice policy and supporting effective implementation of this policy are still not completed. However two recent European Directives: Waste Electrical and Electronic Equipment Directive (WEEE) and End of Life Vehicles Directive (ELV) both contain aspects of IPP ideology. As these two waste streams also contain a significant proportion of plastic waste it is worth taking a closer look at the legislative framework and its potential implications for the plastics recycling industry.

### **10.2.1 Waste Electrical and Electronic Equipment Directive (WEEE) 2002/96/EC**

This legislation was passed on 13 February 2003 but did not come into force in the UK until 2 February 2007.

This directive covers ‘all equipment dependent on electrical currents or electromagnetic fields’. These are set into 10 categories and cover: large household appliances, small household appliances, IT and telecommunication equipment, consumer equipment, lighting equipment, electronic and electrical tools, toys, leisure and sports, medical equipment devices such as dialysis machines, monitoring and control equipment such as smoke detectors and automatic dispensers such as those used for hot and cold drinks and cans.

The WEEE Directive encourages reuse, recycling, recovery and environmental performance. Producers, retailers and distributors are all obliged in differing ways to participate in the disposal of the product.

Producers in the UK are obliged to register, to report UK sales and be financially responsible for collection, recycling and recovery of WEEE.

Retailers and distributors must provide free in-store take back schemes of WEEE and inform the general public of this facility.

There are considerable quantities of plastics that can be recovered from WEEE waste streams which are shown to consist of 22% plastic (Table 10.3).

Plastics form a large percentage of the total waste, and before legislation the recycling percentage of this waste was low. These wastes were landfilled. Therefore, this is potentially an area in which plastics recycling should and can be utilised. Mobile phones for example, have a number of plastic components which are easy to recycle (Figure 10.2).

Table 10.3 Composition of WEEE waste stream	
Material	% wt
Metal: ferrous	49
Metal: non-ferrous	7
Plastic	22
Glass	5
Others	13



**Figure 10.2** Waste Mobile phone mountain (left), mobile phone pieces (right) (*Source: N. Goodship*)

In terms of the IPP policy, this Directive applies the life cycle ethic. What extra burdens would be imposed by a more far-reaching IPP policies are yet to be seen in this sector. However, with this in mind many companies affected by the WEEE Directive are actively involved in IPP work. For example Nokia, Motorola and Vodafone, Panasonic and Seiko Epson are involved in an EU IPP Mobile Phone pilot scheme.

### **10.2.2 End of Life Vehicles Directive (ELV) 200/53/EC**

The major objective of this Directive is one of waste prevention. It seeks to prevent waste from vehicles as well as the reuse and recycling of their components. It was implemented in the UK in 2003 with expanded responsibilities in 2005.

Member states must ensure that producers limit the use of certain hazardous substances in the manufacture of new vehicles. They must also consider a design for environment (DfE) approach to new designs to increase the scope for activities such as recycling. Producers have to pay ‘all or a significant part’ of the costs of treating ELV (whether they have a value or not). Member states have to set up collection systems for ELV and their components, ensuring all vehicles go to authorised treatment facilities with certificates for destruction issues for deregistration. Therefore the last holder of an ELV will be able to dispose of it free of charge with producers meeting a significant if not all of this cost.

Many aspects of this directive contain IPP thinking with the focus on the consideration of the potential for environmental damage throughout manufacture to end-of-life.

IPP thinking has been embraced by a number of manufacturers in the automotive sector (**Figure 10.3**). Examples of this include providing consumers with environmental information about their products by an Environmental Product Declaration (EPD). There are recognised schemes for certifying this data in Sweden, Japan, South Korea, Norway and Canada for example, with Sweden and Japan leading the way. Core information is based on Life Cycle Analysis (LCA) and by compliance with ISO 14025 [4] and standardisation allows direct product comparison.

Whilst at the moment this is not seen by manufactures as an important factor in purchasing decisions by customers, EPD information can be found on a variety of automotive websites including Mercedes-Benz,



**Figure 10.3** Cars (*Source N. Goodship*)

Toyota and Volkswagen. There is a considerable amount of activity by manufacturers in the field of LCA. This was driven specifically by the original demands of the ELV. Enforcing legislation has forced manufacturers to find novel solutions and innovate to survive. It has also allowed companies usually seen as rivals to come together to find ways to best meet demanding environmental targets to retain their place in the European Automotive market.

For plastics recycling this has meant the automotive industry has championed the standardisation of recyclate materials. This will allow manufacturers to have confidence in the use and performance of the recyclate materials they put on new vehicles. This is a significant step in the acceptance of using materials otherwise destined for landfill.

### **10.3 Conclusion**

The continued development of an integrated IPP depends primarily on the political agendas of member states and the inevitably long

time scales involved in implementing these changes. However with the policy at the moment firmly one of ‘eco-friendly’, forthcoming legislation is only likely to force greater environmental compliance and challenges for manufacturers. This is reflected by the large amount of research being carried out now, for example in both the automotive and electrical and electronic industries. By taking this initiative now and embracing LCA and the vision of IPP, whilst simultaneously encouraging a market for environmentally friendly products, the impact of IPP legislation, when it arrives should be minimised for those prepared to act now. The implications for plastics recycling are therefore favourable.

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1. *Plastics Recycling in Perspective*, APME Technical and Environmental Centre, APME, Brussels, Belgium, 2000.
2. *Assessing The Eco-Efficiency of Plastics Packaging Waste Recovery, New Insights Into European Waste Management Choices*, Summary Report, APME, Brussels, 2001.
3. L. Bontoux, F. Leone, M. Nicolai and D. Papameletiou, *The Recycling Industry in The European Union: Impediments and Prospects*, EUR 17271 EN, Report Prepared by IPTS for the Committee for Environment, Public Health and Consumer Protection of the European Parliament, Institute for Prospective Technological Studies, Seville, Spain, December 1996.
4. 150 14025, *Environmental Labels and Declarations – Type 3 Environmental Declarations – Principals and Procedures*, 2006.

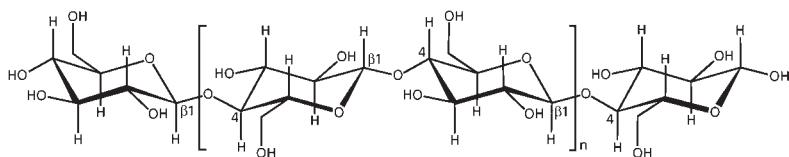
# 11

## Rise of the Biopolymers: Recycling *versus* Degradation

In Chapter 7, the conflict between recycling plastics and causing them to degrade in the environment was briefly discussed in the context of oil based plastics. This chapter is devoted to another naturally biodegradable set of materials called biopolymers.

The polymers discussed up until now have all been made synthetically, however, polymers also occur naturally and are produced by microorganisms, plants and animals. Polymers that are produced by living organisms are called biopolymers. The monomers in this case can be materials such as sugars, amino acids and nucleic acids and by polymerisation can produce starch based polymers or protein based polymers. We have biopolymers inside us all - nucleic acid which produces our own DNA is a biopolymer.

In Chapter 2, a polyethylene polymer was shown to be made of a carbon backbone. This structure is particularly resistant to biodegradability. Because a biopolymer by default must be naturally biodegradable in the environment (otherwise all plants, animals and microorganisms would be here for ever!), its backbone contains other elements such as nitrogen or oxygen. It is this structure that gives these materials their biodegradable nature. This makes them fundamentally different to the degradable plastics discussed in Section 7.6.1. Their chemical structure is also more complex as shown by **Figure 11.1**. Note the oxygen molecules within the structure which give the molecule its biodegradable nature.



**Figure 11.1** Structural unit of cellulose

Three examples of biopolymers are cellulose, starch, and gelatin. Cellulose accounts for 40% of all organic matter and is found in plant cell walls. Starch is found in a number of plants such as corn, potatoes, wheat, rice, barley and peas. Gelatin on the other hand, is extracted from animal bones or animal skins rather than from plants.

To turn these biopolymers into bioplastics is the same as for synthetic polymers:

Biopolymer + additives = bioplastic

Therefore, a bioplastic is a non-toxic, biodegradable plastic made entirely or almost entirely of renewable raw materials.

As plants are more abundant than animals there has been considerable interest in creating modern plant-based bioplastics, especially from plant crop oils. Since crops can simply be replanted and harvested and therefore cannot be depleted, polymers made from these sources are called renewable. While renewable technology such as solar power and wind power is more environmentally friendly than fossil fuel technology, many believe that crops from renewable resources are also a more environmentally alternative to fossil fuels. However, in the case of crop-based plastics the evidence is not convincing at present, and it has been argued that the energy required to convert plants to polymers is actually larger. However, the need to find an alternative



feed stock for future polymer production is a compelling one and one with which it is hard to disagree.

Although polymers made from crop-based plants currently make up only a small percentage of current polymer production, their use and market share is likely to expand rapidly in the next decade. Sales growth of between 20-30% per year suggests these materials will soon be competing with commodity materials [1]. Many polymer manufacturers are actively researching replacing fossil fuel feed stocks, as potentially it removes the price restrictions and uncertainty imposed by the fluctuating price of crude oil. By 2007 forecasts estimate the worldwide manufacturing of these materials will reach 600,000 tonnes. Whilst most polymers are derived from fossil fuel, certain products are already based upon, or incorporate in their formulation, a number of vegetable oil-based derivative products. There appears to be considerable scope for an expansion in the use of vegetable oils and oilseed crops in polymer production. Therefore, throughout the world there are a large number of researchers active in this area, as well as in other product sectors such as paints, detergents, pharmaceuticals and lubricants which utilise oil crops.

One material dominates the worldwide oil crop market. This is rapeseed oil. Whilst this can obviously be used as food, a large percentage goes into non-food applications. Linseed oil is also used in a number of non-food applications and in order to support consumption and potential growth in the EU considerable quantities of vegetable oils have to be imported. Other oilseeds of importance include sunflower and soya.

The value and use of different vegetable oils in non-food applications depends on their composition. For polymer production this means long carbon chain lengths are needed. The major use of biopolymers has so far been in the packaging industry, with plastics made from using sugar beet (to produce polygonic acid) or starch to produce polylactic acid (PLA). Starch can also be used

to produce polycaprolactone (PCL) or polyvinyl alcohol (PVA). If bioethanol is produced, plastics such as polyethylene can be produced. Products manufactured from these products include food trays and thin films for wrapping.

The main advantages in using biopolymers in the environment is biodegradability, although some of these materials are also compostable.

To biodegrade they are broken down into carbon dioxide and water by microorganisms.

To be compostable the biomaterial requires a controlled microbial environment such as an industrial compost facility before they will degrade. This is because there are requirements of heat, moisture and aeration to activate and sustain the degradation process. To be considered compostable, a material must be able to be put into an industrial composting process and breakdown by 90% within six months. Under the European Standard EN 13432 [2] they can be labelled or marked with a 'compostable' symbol.

As an example a PLA film under 20  $\mu\text{m}$  thick is compostable and packaging made and marked with this symbol can be commercially composted. Thicker films above 20  $\mu\text{m}$  although still biodegradable do not qualify as compostable. A home composting logo has yet to be established. However, at some point in the future this will enable consumers to dispose of compostable packaging directly on their own compost heap. At the moment plastics can only be disposed of in industrial compost units.

When comparing the use of a fossil fuel derived polyethylene bag with a biodegradable vegetable-based bag, they are pros and cons for the use of both.

Oil-based polyethylene can be made biodegradable by the use of additives (Section 7.6.1). This is a well known, commercially

used, proven technology and provides controlled degradation of waste. There is no performance difference in service compared to conventional bags, but they breakdown faster at the end of life. However, they are made of fossil fuels. If placed in landfill, degradation can be very slow, as degradation needs heat and sunlight. As the weather and climate is varied and unpredictable, so is degradation. They cannot be composted and if mixed in with recyclable plastics can decrease the value of such materials.

Commercially, biodegradable polyethylenes of this type are used in applications such as bin liners, carrier bags, agricultural film and mulch film.

An alternative is to use a biopolymer. In a similar film application for example, an option would be to use one that is starch-based and derived from corn (PCL, PVA or PLA). These biodegradable films, dependent on thickness, would meet the ASTM standard (American Standard for Testing Materials) and European [EN13432] for composting. However these materials require a controlled microbial environment such as an industrial compost facility before they will degrade.

In this case the waste would be both biodegradable and compostable and require no (or less) fossil fuel. However there are potential downsides. Generally, these materials have lower mechanical strength than conventional bags, a slow degradation in standard landfill sites, a limited shelf life (before degradation begins), and it would reduce the value of recycled material if material found its way into the supply chain and contaminated it. This is a major issue with keeping biodegradable plastics separate from recycling infrastructure. Further, any composting would need to be done in a special composting facility until composting infrastructure and legislation is finalised.

At the moment the current plastic recycling infrastructure is unable to cope with the extra demands caused by also having a waste stream of biodegradable materials. The two plastic recovery mechanisms cannot be mixed, since it is impossible to separate biodegradable from non-biodegradable materials at present.

Therefore the choice of which type of material to use for any application would need careful consideration.

As well as the direct production of polymers, vegetable oil derivatives have other uses in the polymer industry, for example as additives. Materials made from vegetable oil have many uses and are used to produce anti-static, slip, and plasticising agents, stabilisers, processing aids and as flame retardants (see Section 2.4.). They can also be incorporated into the manufacture of polyamides, polyesters and polyurethanes.

Markets already exist and are expanding for biodegradable plant derived polymers. Further growth areas include using plant fibres as fillers for production of biodegradable composite materials. The automotive industry especially is taking an interest in this area and a number of current commercially available models feature composite panels of this type.

What the future may hold is unclear but one idea that has been suggested is that of using genetic engineering to produce polymers directly within the plant itself. The potential of biopolymers has certainly captured public imagination and therefore we can expect to see massive growth in biopolymer sales worldwide. However, how it will co-exist with existing recycling infrastructure is yet to be seen.

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## **Suggested Further Reading**

3. E. S. Stevens, *Green Plastics*, Princeton University Press, Princeton, NJ, USA, 2002.



# Abbreviations and Acronyms

APC	American Plastics Council
APME	Association of Plastics Manufacturers in Europe
ASTM	American Society for Testing Materials
BPF	British Plastics Federation
CARE	Consortium for Automotive Recycling
DFD	Design for Disassembly
DfE	Design for Environment
DFR	Design for Recycling
DNA	Deoxyribonucleic acid
DSC	Differential scanning calorimetry
DSD	Duales System Deutschland
ELV	End of Life Vehicle(s) Directive
EPD	Environmental Product Declaration
EPS	Expanded polystyrene
EU	European Union
GMT	Glass mat transfer
HALS	Hindered amine light stabilisers
HDPE	High-density polyethylene
HIPS	High impact polystyrene
IPP	Integrated Product Policy

IR	Infrared
ISO	International Organization for Standardization Method
IT	Information Technology
L/D	Length/diameter ratio
LCA	Life cycle analysis
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MFI	Melt flow index
MPW	Mixed plastic waste
NIR	Near infra-red
PA	Polyamide
PA6	Polyamide 6
PA66	Polyamide 66
PCL	Polycaprolactone
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	Polylactic acid
PMMA	Polymethyl methacrylate
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVA	Polyvinyl alcohol
PVC	Polyvinyl chloride
R&D	Research and Development
RRECOM	Recycling and Recovery from Composite Materials
SMC	Sheet moulding compound



## *Abbreviations and Acronyms*

SPI	Society of the Plastics Industry
T <sub>m</sub>	Melting point
UV	Ultraviolet
WEEE	Waste Electrical and Electronic Equipment Directive
WKR	Wormser Kunststoff Recycling GmbH, Germany
WRAP	Waste and Resources Action Program
XRF	X-ray fluorescence



# Glossary

Additive	A material added to the polymer to increase its functionality or reduce costs.
Agglomeration	A process to increase the bulk density of the polymer.
Biodegrade	To be broken down into carbon dioxide and water by microorganisms.
Bioplastic	A material made up of biopolymer and other biodegradable additives.
Biopolymer	A naturally occurring polymer found in micro organisms, plants and animals.
Blow moulding	A process for production of hollow articles such as bottles.
Cellulose	Naturally occurring biopolymer, found in plants.
Chemical recycling	A process to create petrochemical feedstock from plastics.

Co-injection moulding	A variation of injection moulding that uses two materials instead of one to create a sandwich structure.
Commingled	Mixed plastics.
Compatibiliser	An additive that chemically ‘glues’ materials together.
Compostable	To be compostable a biomaterial requires a controlled microbial environment such as an industrial compost facility before they will degrade.
Degradation	Molecular breakdown of a polymer, for example, by the action of shear, light or heat.
Design for recycling	New component design that takes into account disposal.
Die	The part of an extruder where the material exits.
Energy recovery	Burning waste materials to recover energy in the form of electricity and heat.
Extrusion	A processing technique for thermoplastics used to produce granules, pipes, sheets or profiles.
Gelatin	Naturally occurring biopolymer, found in animal bones and skins.

Heterogeneous	A material with two or more phases.
Homogeneous	A material with the same properties at all points.
Hygroscopic	Materials that absorb moisture.
Feedstock recycling	<i>see Chemical recycling.</i>
Injection moulding	A mechanical process for making complex plastic parts.
Intrusion moulding	A mechanical recycling process suitable for mixed plastics, where molten materials are fed into simple moulds.
Mechanical recycling	The act of grinding and reprocessing plastic material.
Melt filtration	Sieving of melts to remove contaminants.
Melt flow index	A test for measuring how viscous a material is at standard conditions.
Mixed plastic waste (MPW)	A mixture of different waste plastics.
Monomer	The chemical building blocks from which polymers are produced.
Parison	The extrudate from a blow moulder before inflation.

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Phase	A physically homogeneous, mechanically separable portion of a material system.
Plastic	A mixture of polymer and additives.
Polyamide	A type of thermoplastic material.
Polycaprolactone (PCL)	Biopolymer made from starch.
Polyethylene	A type of thermoplastic material often used for packaging. Common grades include high density (HDPE), low density (LDPE) and linear low density (LLDPE).
Polylactic acid (PLA)	Biopolymer made from starch.
Polymer	A macromolecule built from many monomer units.
Polymerisation	The process by which monomers form into polymers.
Polypropylene	A type of commodity thermoplastic material.
Polystyrene	A type of commodity thermoplastic material.
Polyvinyl alcohol (PVA)	Biopolymer made from starch.
Primary recycling	‘In house’ mechanical recycling.
Prime	Grade of plastic consisting primarily of polymer.

Quarternary recycling	Incineration of waste for energy recovery.
Reclaim	Material reclaimed from the waste stream for recycling.
Recyclate	Material that has already been processed.
Re-use	Using a part again in its original form.
Rheology	Study of deformation and flow.
Secondary recycling	Mechanical recycling that is not 'in-house'.
Shot weight	The amount of material used to make a single injection moulding.
Stabiliser	A type of additive used to protect a polymer from degradation.
Starch	Naturally occurring biopolymer, found in plants.
Tertiary recycling	<i>see Chemical recycling</i>
Virgin	Material that has not yet been processed.





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